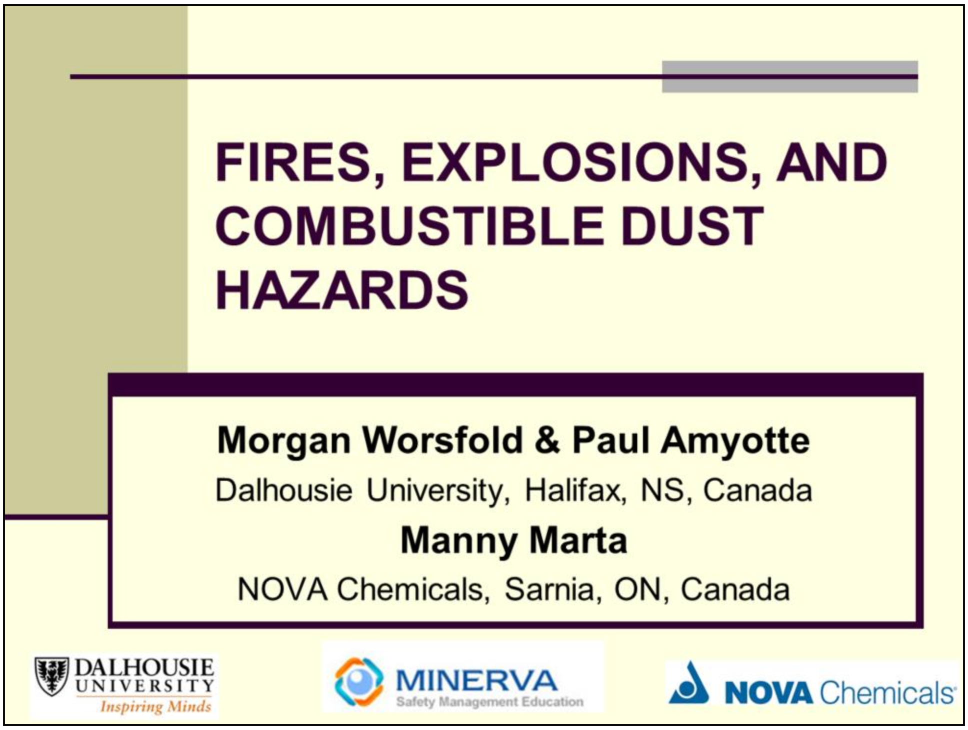


This educational module on Fires, Explosions, and Combustible Dust Hazards was developed by MASc candidate Morgan Worsfold. The project was conducted under the supervision of Dr. Paul Amyotte and with the industrial mentorship of Mr. Manny Marta. Funding in the form of a Mitacs grant was provided by Minerva Safety Management Education.

The module is designed for use in either of two ways. First, the slides can be shown as a presentation to multiple participants in a workshop/seminar format. The presenter would first gain familiarity with the slide material by reviewing the content of the notes page accompanying each slide. Second, the module can be completed by an individual in a self-study format. In this case, the “notes page” feature of PowerPoint would enable the participant to view the slides and accompanying notes at the same time.

Module Basics

- Scope
  - Fires, explosions, and combustible dust hazards
- Motivation
  - While these incidents and hazards are prevalent in the process industries, practitioner knowledge gaps exist
- Objective
  - Achievement of specific learning objectives by the target audience of undergraduate engineering students

2

The module introduces undergraduate engineering students to the fundamentals of process fires and explosions, with an emphasis on combustible dust hazards and the prevention and mitigation of dust explosions.

Combustible dust hazards – in spite of their potentially severe explosion consequences – are not well-known or understood by many industrial practitioners. Improved education and communication avenues are key to creating heightened awareness. This particular module is aimed at raising awareness within one group of people in need of this information – undergraduate engineering students. Specific learning objectives have been developed as indicated in the next two slides.

Learning Objectives

- Remembering
  - Define combustible dust
  - Identify the three elements of the fire triangle and the five elements of the explosion pentagon
- Understanding
  - Explain how gaseous, liquid and solid fuels burn
  - Describe the fundamentals of a dust explosion according to the explosion pentagon
- Applying
  - Calculate the airborne concentration resulting from the dispersion of a dust, given its bulk density, layer thickness and enclosure height

3

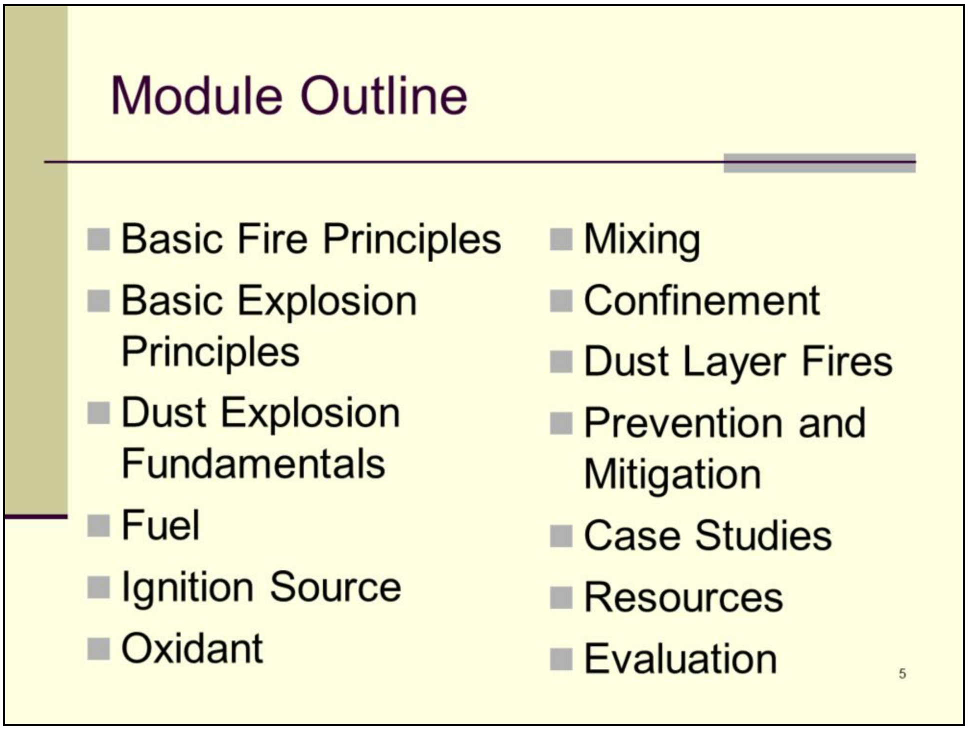
This slide shows the module learning objectives for the first three levels in Bloom's Taxonomy. The evaluation section at the end provides a test of whether these learning objectives have been achieved following completion of the module.

Learning Objectives (Continued)

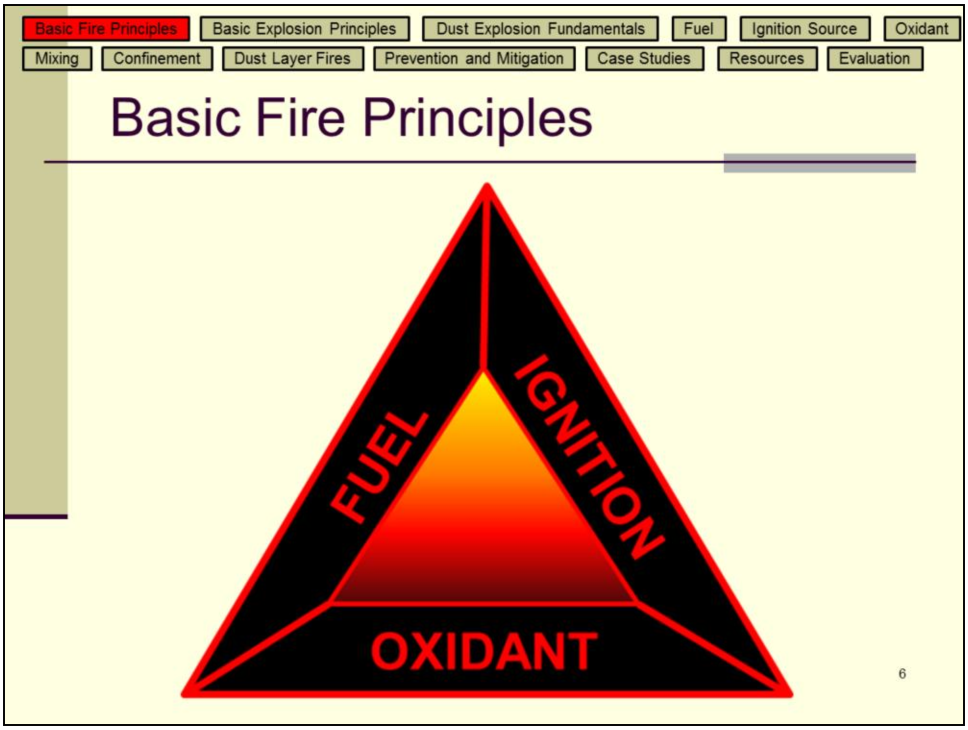
- Analyzing
  - Identify combustible dust hazards in a given example
- Evaluating
  - Determine appropriate prevention and mitigation strategies for a specific case study and explain reasoning
- Creating
  - Formulate a dust explosion prevention plan for a given scenario, taking into account each element of the explosion pentagon

4

This slide shows the module learning objectives for the next three levels in Bloom’s Taxonomy. The evaluation section at the end provides a test of whether these learning objectives have been achieved following completion of the module.

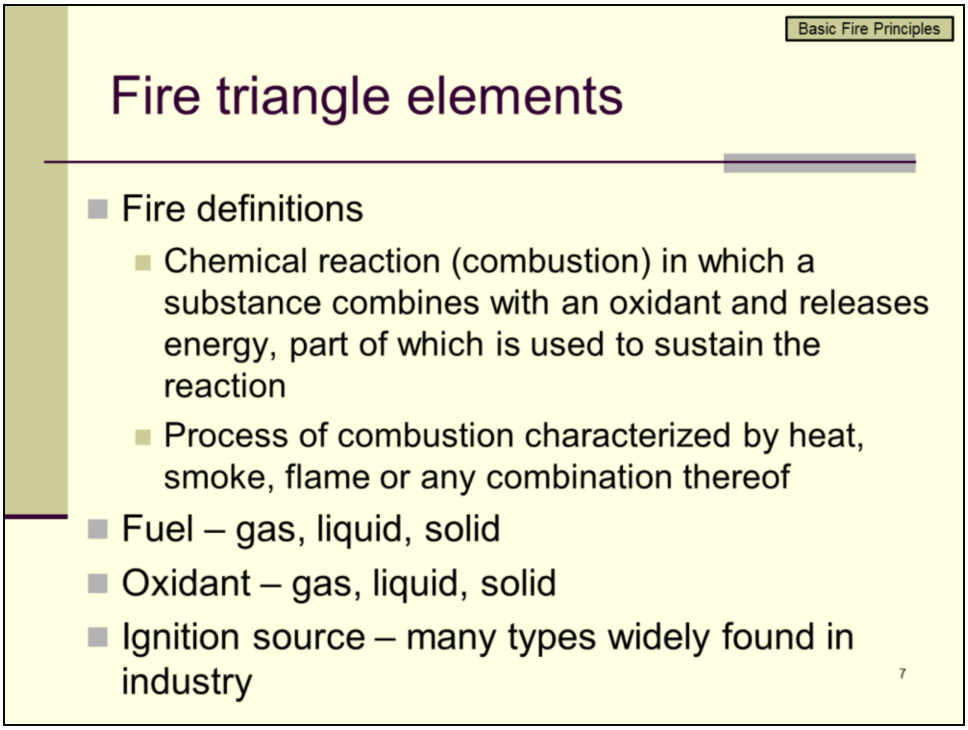


The module first provides an overview of the basic principles of fires and explosions. Dust explosion fundamentals are then introduced, followed by an examination of the five requirements for a dust explosion: fuel, ignition source, oxidant, mixing and confinement. The issue of dust layer fires is briefly covered and considerable time is spent discussing techniques for the prevention and mitigation of dust explosions. Three case studies are presented, helpful resources are indicated, and an evaluation of the achievement of learning objectives is conducted.



In this section we introduce some of the basic principles of fires. We begin with a look at the three elements of the fire triangle. Various flammability parameters are defined and the consequences of concern for fires are described. The section concludes with an examination of the types of fires typically encountered in the process industries, as well as examples of large-scale fires that have impacted our understanding of these events.

Much of the material in this section is drawn from the following reference:
Crowl, D. A. and Louvar, J. F., “Chemical Process Safety. Fundamentals with Applications”, 3rd edition, Prentice Hall PTR, Upper Saddle River, NJ (2011).

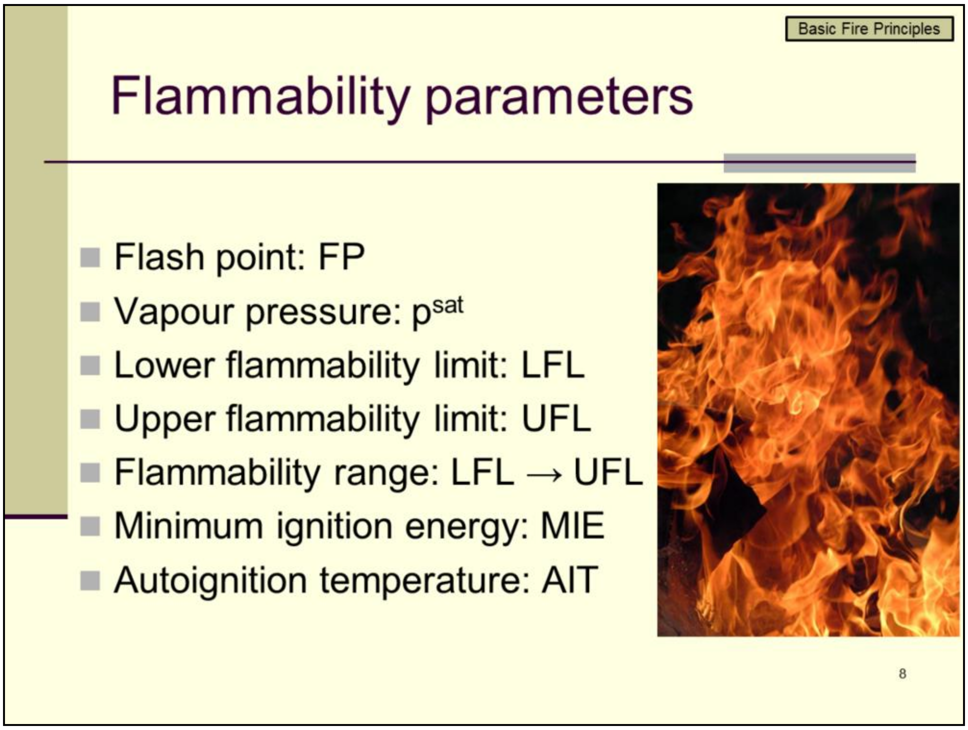


The first definition of a fire comes from Crowl and Louvar (2011). This definition has the advantage of addressing the need for continuing reaction beyond the initial fuel/oxidant ignition. This additional requirement of a chemical chain reaction is sometimes represented as a fourth criterion in what is known as the fire tetrahedron. The second definition of a fire has been proposed by the UK Institution of Chemical Engineers, or IChemE, and has the advantage of addressing key consequences of concern for fires: damaging heat fluxes, toxic combustion products, and direct flame impingement.

The fuel for a fire can be in any of the gaseous, liquid or solid states. Examples include gasoline, wood dust and propane, respectively (Crowl and Louvar, 2011). Regardless of the original fuel state, actual combustion occurs homogeneously in the vapour phase. This is of course not an issue for gaseous fuels, but it means that liquid and solid fuels must first undergo phase transitions to vapours before combustion can occur. The heterogeneous combustion of fine carbon powder is one of the few exceptions to this requirement.

The oxidant also can be in any of the gaseous, liquid or solid states. Examples include fluorine, hydrogen peroxide and ammonium nitrite, respectively (Crowl and Louvar, 2011). By far, the most prevalent oxidant is oxygen – either on its own or more commonly in the ambient air.

Ignition sources are varied and widely available in industry. Common sources include open flames, hot surfaces, electric sparks and electrostatic discharges. In theory, removal of **any one** of the fire triangle elements will prevent a fire from occurring. In practice, however, reliance on removing **only one** of these elements is not undertaken as a primary line of defense against fires. This is especially the case for ignition sources.



It is important to recognize that, for the most part, the flammability parameters shown on this slide are not intrinsic material properties. However, when determined by qualified personnel using standardized test procedures and standardized equipment, they afford the best available information for understanding fire behaviour. The parameters presented here relate to the likelihood of occurrence component of risk.

Flash point (FP) is defined as the lowest temperature at which a liquid gives off sufficient vapour to form an ignitable mixture with air (Crowl and Louvar, 2011). From a safety perspective, one would want the flash point of a liquid fuel to be high. It should be noted that the flash point of some materials (e.g., octane with FP = 13.3 °C) is such that the risk will vary depending on geographical location and ambient conditions.

Vapour pressure (p^{sat}) is defined as the equilibrium pressure of a vapour above its liquid in a closed container. Although called “vapour” pressure, p^{sat} is a property of the liquid phase. It can be thought of as the driving force for evaporation of a liquid; therefore, from a safety perspective, one would want the vapour pressure of a liquid fuel to be low.

Gases, and vapours generated from liquids, are flammable only between certain concentrations (typically specified as volume percentages in air). The lowest concentration at which such fuels will burn is called the lower flammability (flammable) limit (LFL), or the lean limit. Similarly, the highest concentration at which such fuels will burn is called the upper flammability (flammable) limit (UFL), or the rich limit. The spread between the lower and upper limits is the flammability range. Ideally the LFL will be high and the flammability range narrow. Fortunately, the flammability range is indeed narrow for most hydrocarbons (e.g., 2.2 % - 9.5 % for propane). Acetylene on the other hand has a wide range from 2.5 % - 80.0%.

Minimum ignition energy (MIE) is the lowest electric spark energy that will ignite a given fuel/air mixture. Autoignition temperature (AIT) applies to a different ignition scenario, and is defined as the temperature above which sufficient energy is available in the oxidizing environment to ignite a given fuel/air mixture.

In later sections of the module we will look at other parameters such as limiting oxygen concentration

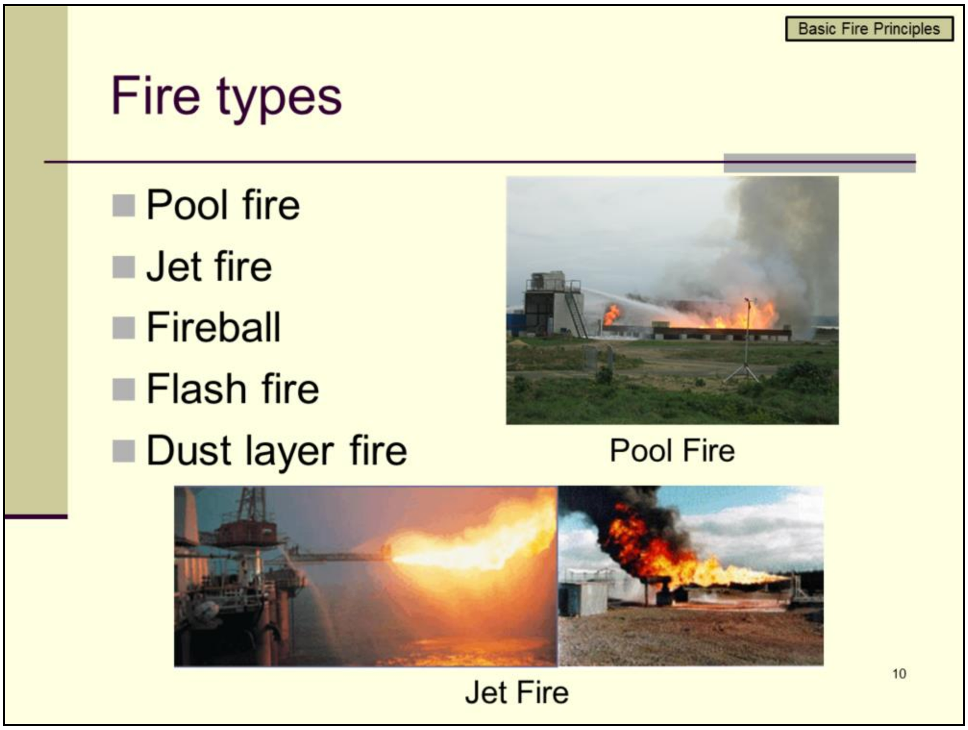
(LOC), and direct counterparts to the above parameters when the fuel is a combustible dust.

There are several consequences that can result from a process fire.

Flame temperatures for many materials (e.g., solvents) are around 1000 °C (Crowl and Louvar, 2011). Direct flame impingement is therefore extremely harmful. Given the magnitude of these temperatures, radiation is a dominant heat transfer mechanism and heat fluxes can rapidly escalate to levels where damage occurs (e.g., cabling can be damaged by a heat flux of only 2 kW/m^2). Additionally, smoke and other combustion products (some toxic) can impair human health and impede evacuation and rescue efforts.

The slide shows two sides of a poster handed out by a concerned citizens group at the April 19, 2013 public hearing of the US Chemical Safety Board in the matter of the Chevron Richmond Refinery fire. Quoting from the CSB investigation report (CSB, "Interim Investigation Report. Chevron Richmond Refinery Fire", U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2013)):
On August 6, 2012, the Chevron U.S.A. Inc. Refinery in Richmond, California, experienced a catastrophic pipe failure in the #4 Crude Unit. The pipe ruptured, releasing flammable, hydrocarbon process fluid which partially vaporized into a large vapor cloud that engulfed nineteen Chevron employees. All of the employees escaped, narrowly avoiding serious injury. The flammable portion of the vapor cloud ignited just over two minutes after the pipe ruptured. The ignition and subsequent continued burning of the hydrocarbon process fluid resulted in a large plume of unknown and unquantified particulates and vapor traveling across the Richmond, California, area. In the weeks following the incident, approximately 15,000 people from the surrounding area sought medical treatment due to the release.

On "one side" of the poster, you can see the refinery flare on the right and the hydrocarbon combustion plume on the left. The "other side" of the poster gives a sober reminder of the fragile social license under which the chemical process industries operate.



Some of the more common process fires are identified in this slide. The handbook by Nolan is a helpful resource on this topic: Nolan, D.P., “Handbook of Fire and Explosion Protection Engineering Principles for Oil, Gas, Chemical, and Related Facilities”, 2nd edition, Gulf Professional Publishing/Elsevier, Burlington, MA (2011). Also helpful is the guideline produced by the Center for Chemical Process Safety of the American Institute of Chemical Engineers: CCPS, “Guidelines for Protection in Chemical, Petrochemical, and Hydrocarbon Processing Facilities”, American Institute of Chemical Engineers, New York, NY (2003).

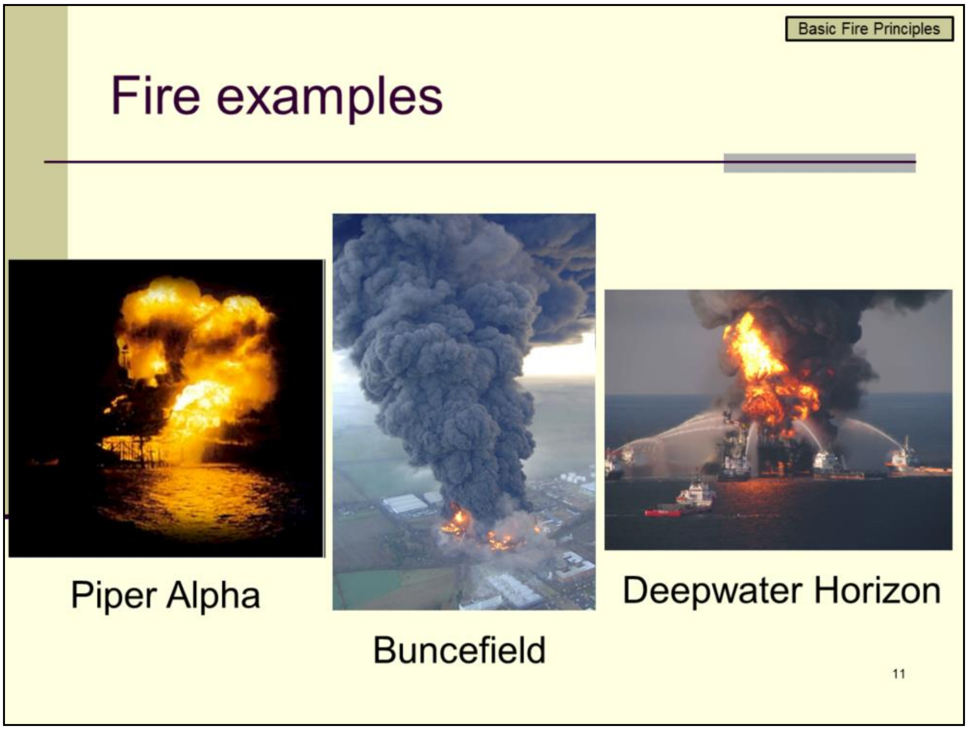
As the name implies, a pool fire occurs when a pool of liquid (actually the vapour just above the liquid surface) ignites. Further vapour is rapidly generated form the pool as it is heated by the flame through convective and radiative transfer mechanisms (Nolan, 2011).

A jet fire is a pressurized stream of combustible gas or atomized liquid that is burning, such as might occur as a result of a rupture in a high-pressure pipeline (Nolan, 2011). Strong momentum vectors are associated with jet fires.

A fireball is defined in CCPS (2003) as *an intense spherical flame resulting from a sudden release of pressurized liquid or gas that is immediately ignited*. Fireballs are most commonly caused by BLEVEs, which are described in the next module section.

A flash fire occurs when a combustible gas release forms a plume or cloud that is not immediately ignited. The cloud will disperse according to the prevailing weather conditions; if ignition occurs without an ensuing explosion, the cloud will burn as a flash fire that rapidly consumes the gas (Nolan, 2011). Under these circumstances, the degree of confinement plays a key role in determining whether a flash fire or vapour cloud explosion occurs. Flash fires can also occur with combustible dusts, as discussed later in the module.

Dust layer fires are covered in a later section of the module.

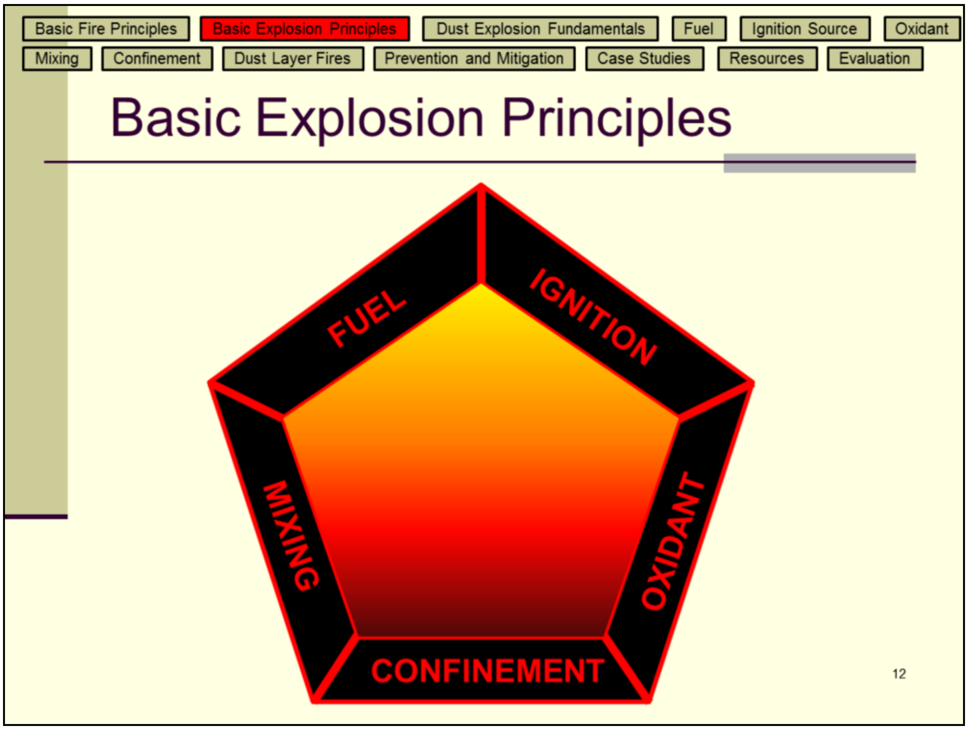


This slide shows three major process incidents involving fires that were all initiated by explosions. Numerous references are available for each incident; a simple internet search will generate multiple sources.

Piper Alpha was an offshore production platform in the North Sea. On July 6, 1988, explosions and subsequent oil and gas fires killed 167 men and destroyed the facility.

Buncefield is an oil storage depot in Hertfordshire, UK. On December 11, 2005, a petrol (gasoline) vapour cloud explosion and subsequent fire caused several injuries, significant asset damage, and substantial business interruption.

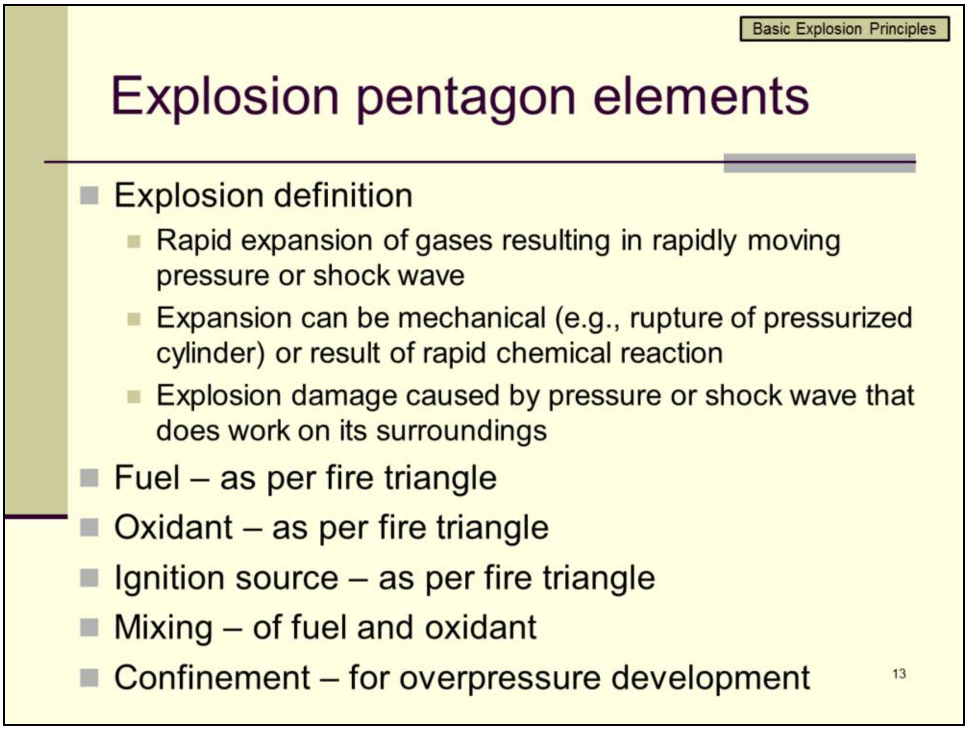
Deepwater Horizon was an offshore production platform in the Gulf of Mexico. On April 20, 2010, a gas explosion and ensuing fire killed 11 workers and caused enormous environmental losses.



In this section we introduce some of the basic principles of explosions. We begin with a look at the five elements of the explosion pentagon. Various explosibility parameters are defined and the consequences of concern for explosions are described. An examination is then undertaken of the types of explosions typically encountered in the process industries, as well as examples of large-scale explosions that have impacted our understanding of these events. The section concludes with an explanation of the relationship between fires and explosions, and the importance of considering whether domino or knock-on effects are possible in a given scenario.

Note that confinement does not need to be complete for a fast-burning flame to transition to an explosion, regardless of fuel type. Partial confinement and turbulence-generating obstacles leading to a high degree of congestion can also be effective in this regard. These points are further explained later in the module.

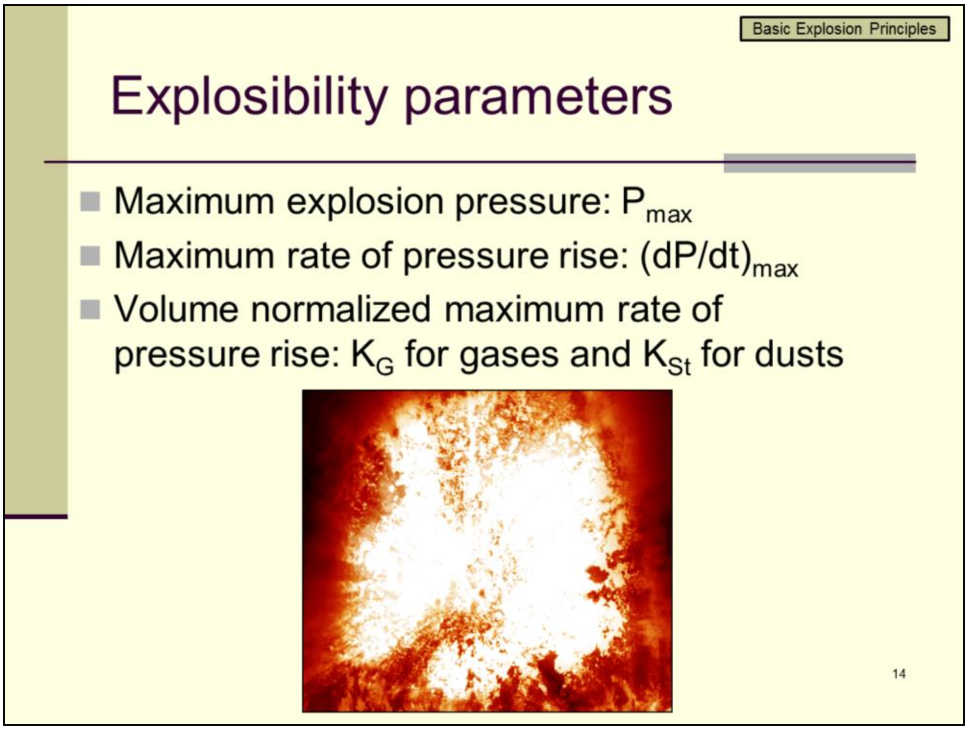
Much of the material in this section is drawn from the following reference:
Crowl, D. A. and Louvar, J. F., "Chemical Process Safety. Fundamentals with Applications", 3rd edition, Prentice Hall PTR, Upper Saddle River, NJ (2011).



The defining features of an explosion are drawn from Crowl and Louvar (2011). Perhaps the most fundamental point to be made is that thermodynamically, in moving from the initial pre-explosion state to the final post-explosion state, mechanical work is done by the exploding system on its surroundings. This is primarily what distinguishes a fire from an explosion. (See also the second-last slide in this section where this distinction is made in the equivalent terms of energy release rate.)

The explosion pentagon includes the three elements of the fire triangle, with the two additional requirements of mixing of the fuel and oxidant, and sufficient confinement of the reacting mixture to generate a destructive overpressure.

The explosion pentagon elements are examined later in considerable detail for the unique category of explosions involving combustible dust.



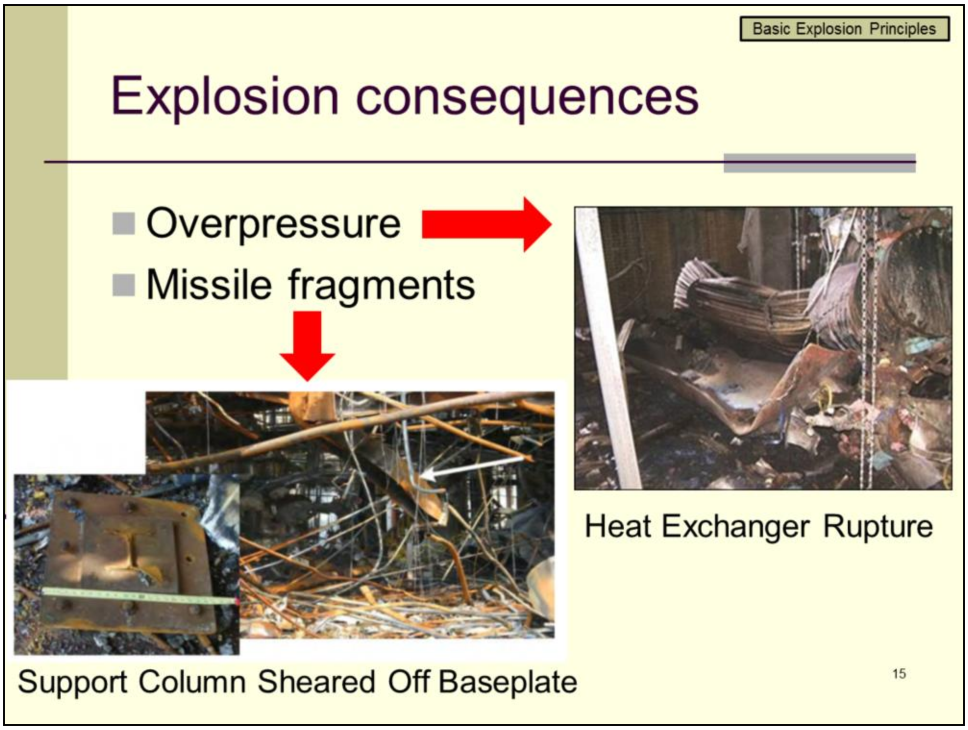
As was the case for the flammability parameters discussed in the previous section, it is important to recognize that the explosibility parameters shown on this slide are not intrinsic material properties. However, when determined by qualified personnel using standardized test procedures and standardized equipment, they afford the best available information for understanding explosion behaviour. The parameters presented here relate to the severity of consequences component of risk.

Many of the other parameters discussed in the previous section on flammability are applicable to the current consideration of explosibility parameters (although from the perspective of likelihood of occurrence of an explosion). This would include, for example, the lower flammability limit (LFL) and minimum ignition energy (MIE).

Maximum explosion pressure (P_{max}) is the peak overpressure attained in a constant-volume explosion by a given fuel/air system. P_{max} is a thermodynamic parameter that depends largely on the initial and final conditions of the reacting mixture. Typical units of P_{max} are bar(gauge) or bar(g).

Similarly, maximum rate of pressure rise ($(dP/dt)_{max}$) is the peak rate of pressure rise attained in a constant-volume explosion by a given fuel/air system. $(dP/dt)_{max}$ is a kinetic parameter that can be significantly influenced by mixture and boundary conditions enroute to the completion of reaction. Typical units of $(dP/dt)_{max}$ are bar/s.

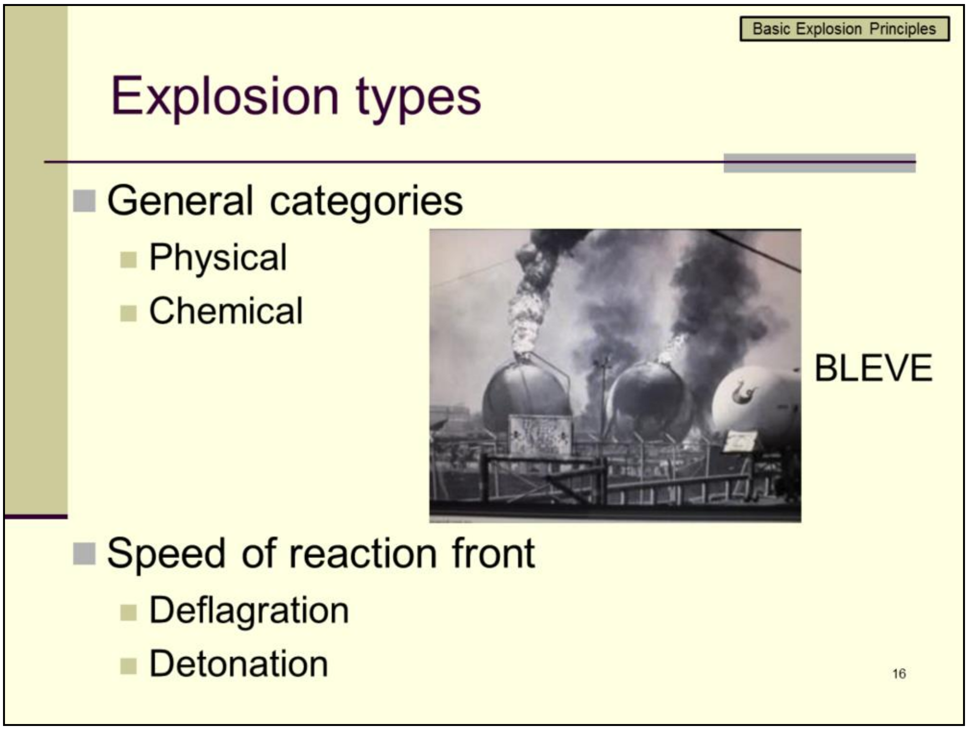
Rates of pressure rise are of course dependent on the volume in which the explosion occurs. In an attempt to volume-normalize the maximum rate of pressure rise, a cubic relationship has been developed to define the parameters K_G (for gases) and K_{St} (for dusts) as the product of the maximum rate of pressure rise and the cube-root of the volume in which the explosion occurs. Units of K_G and K_{St} are therefore bar·m/s. A full explanation of the use and validity of the cubic relationship is beyond the scope of the current module.



As previously described, it is the work done by the pressure or shock wave that causes damage in an explosion. Destructive overpressures can threaten the integrity of the enclosure in which the explosion occurs, or can travel over distance and damage nearby equipment. An additional consequence could be the generation of missile fragments that can cause structural damage and harm to personnel. Also, consequences related to flame, heat and smoke will be pertinent if the explosion involves combustible material.

The right-hand photograph in the slide shows some of the damage resulting from overpressurization and subsequent rupture of a heat exchanger. There was no chemical reaction involved in this explosion.
(Source: CSB, "Case Study. Heat Exchanger Rupture and Ammonia Release in Houston, Texas. The Goodyear Tire and Rubber Company", No. 2008-06-I-TX, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2011).)

The lower photograph in the slide shows damage that occurred as a result of a runaway chemical reaction and subsequent explosion of a residue treatment tank. Missile fragments from the tank struck the structural column (indicated by the white arrow in the photograph), shearing the column off from the steel baseplate also shown in the photograph.
(Source: CSB, "Investigation Report. Pesticide Chemical Runaway Reaction. Pressure Vessel Explosion. Bayer CropScience, LP", Report No. 2008-08-I-WV, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2011).)

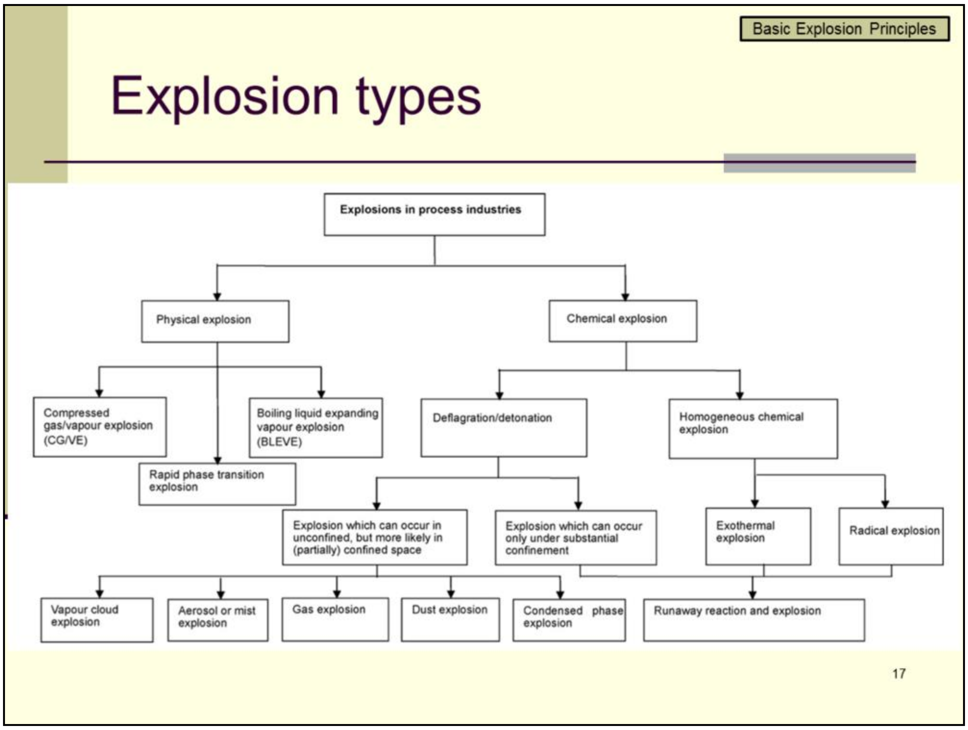


The broadest way to categorize explosions is by whether there is a chemical reaction involved. Physical (or mechanical) explosions result from the sudden failure of a vessel containing a non-reactive gas under high pressure (Crowl and Louvar, 2011). Chemical explosions, as the name implies, involve a chemical reaction. As we will see shortly, a dust explosion is a chemical explosion because it involves a chemical reaction – in this case, a propagating combustion reaction that is transmitted spatially through the reaction mass.

A somewhat special class of explosion is the BLEVE – Boiling-Liquid Expanding-Vapour Explosion. An excellent description of this event is given by Crowl and Louvar (2011):
A BLEVE occurs if a vessel that contains a liquid at a temperature above its atmospheric pressure boiling point ruptures. The subsequent BLEVE is the explosive vaporization of a large fraction of the vessel contents; possibly followed by combustion or explosion of the vaporized cloud if it is combustible. This type of explosion occurs when an external fire heats the contents of a tank of volatile material. As the tank contents heat, the vapor pressure of the liquid within the tank increases and the tank's structural integrity is reduced because of the heating. If the tank ruptures, the hot liquid volatilizes explosively.

Thus, a BLEVE may be a purely physical explosion with no chemical reaction if the liquid is non-reactive. If, however, the liquid is combustible, then the physical phenomena associated with a BLEVE will quickly devolve to a reaction scenario that leads to a chemical explosion and/or fireball. This is essentially the situation depicted in the photograph shown in the slide. On November 19, 1984, the PEMEX LPG (Liquefied Petroleum Gas) terminal in Mexico City experienced a series of BLEVEs that resulted in over 600 fatalities and over ten times that number in injuries.

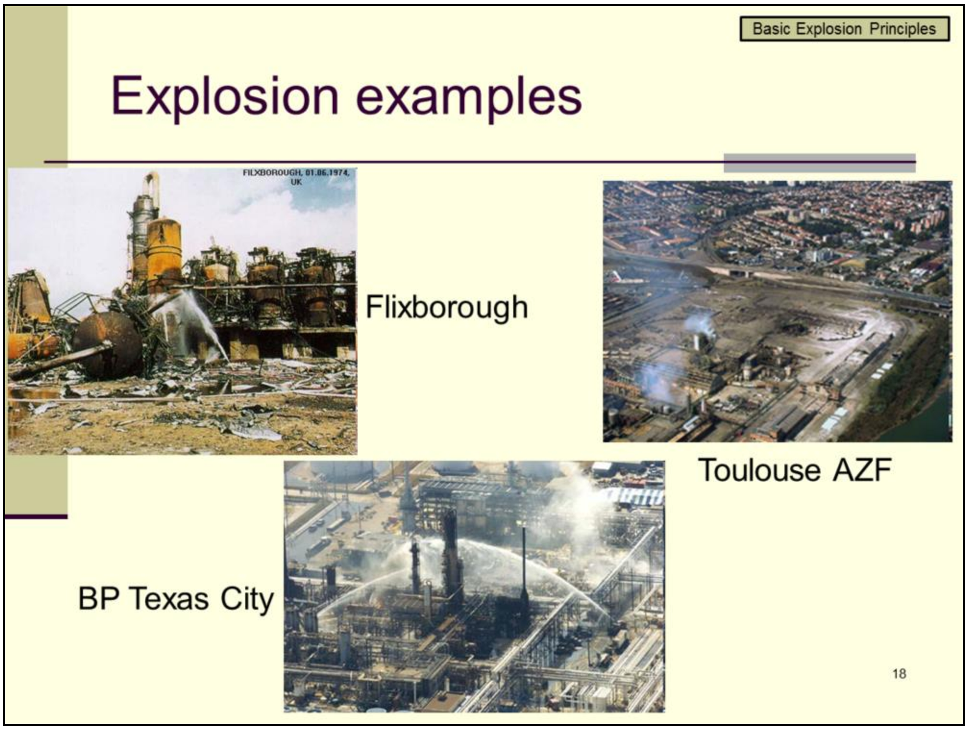
For chemical explosions, a further distinction based on the speed of the reaction (flame) front is important. In a deflagration, the reaction front travels at subsonic speed; in a detonation, the reaction front moves at sonic or supersonic speed (relative to the speed of sound in the unreacted medium). Thus, a deflagration is characterized by the flame front trailing behind the shock wave produced by the explosion; detonations involve coupling of the reaction front and shock wave and can lead to overpressures significantly higher than those experienced with deflagrations.



The classification scheme given in this slide has been proposed by: Abbasi, T., Pasman, H.J. and Abbasi, S.A., “A Scheme for Classification of Explosions in the Chemical Process Industry”, Journal of Hazardous Materials, **174**, 270-280 (2010).

Look back over the past few slides in this section. You should find that the current slide is generally consistent with the previous discussion.

The next module section commences our detailed examination of dust explosions. According to the above figure from Abbasi et al. (2010), dust explosions are chemical explosions that occur as either deflagrations or detonations and are more likely to occur in an at least partially confined space than in an unconfined environment. The only caveat we would add to this description is that dust detonations, although not unknown, are quite uncommon. The vast majority of dust explosions occur as deflagrations.

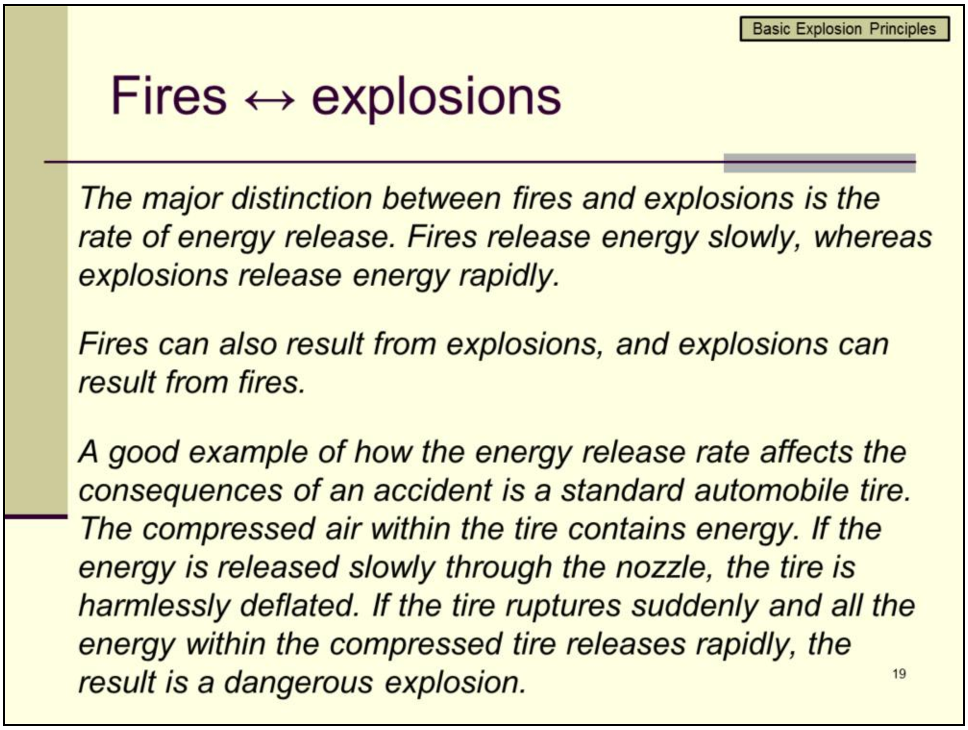


This slide shows three major process incidents involving explosions. Numerous references are available for each incident; a simple internet search will generate multiple sources.

The Flixborough (UK) Works of Nypro Limited was a manufacturer of caprolactam – a raw material for nylon production (Crowl and Louvar, 2011). On June 1, 1974, a cyclohexane vapour cloud explosion killed 28 workers, injured 36 others, and destroyed the facility.

AZF operated a fertilizer plant in Toulouse, France. On September 21, 2001, an ammonium nitrate explosion killed 31 people, injured countless others, and caused significant damage at the plant site and in the surrounding community.

The BP Texas City Refinery is located in Texas City, Texas. On March 23, 2005, a hydrocarbon vapour cloud explosion occurred, killing 15 workers, injuring 180 other people, and causing widespread facility damage.



This slide gives three quoted passages from Crowl and Louvar (2011). The explanations and analogies are complementary to the discussion in the current and previous module sections.

Fires are different from explosions; both, however, can cause harm to people, asset damage, business interruption, and degradation of the environment.

Basic Explosion Principles

Domino effects

Primary Scenario	Escalation Vector	Expected Secondary Scenario[a]
Pool fire	Heat radiation, fire impingement	Jet fire, pool fire, BLEVE, toxic release
Jet fire	Heat radiation, fire impingement	Jet fire, pool fire, BLEVE, toxic release
Fireball	Heat radiation, fire impingement	Tank fire
Flash fire	Fire impingement	Tank fire
Mechanical explosion[b]	Fragments, overpressure	All[c]
Confined explosion[b]	Overpressure	All[c]
BLEVE (boiling liquid expanding vapour explosion)[b]	Fragments, overpressure	All[c]
VCE (vapour cloud explosion)	Overpressure, fire impingement	All[c]
Toxic release	–	–

[a]Expected scenarios also depend on the hazards of the target vessel inventory.
[b]Following primary vessel failure, further scenarios may occur (e.g., pool fire, fireball, toxic release).
[c]Any of the scenarios listed in the first column (primary scenario) may be triggered by the escalation vector.

20

The table in this slide is drawn from: Cozzani, V., Gubinelli, G. and Salzano, E., "Escalation Thresholds in the Assessment of Domino Accidental Events", Journal of Hazardous Materials, **129**, 1-21 (2006).

We present this slide to further illustrate the relationship between fires and explosions (as well as toxic releases, which are outside the scope of the current module). An additional objective is to summarize the module content to this point before moving on to specific discussion of dust explosions. There is a lot of information in this slide; study it carefully to reinforce your understanding of the basic principles of fires and explosions.

Domino or knock-on effects occur when a "primary" event propagates by means of an escalation vector to nearby equipment or facilities, and triggers one or more "secondary" events. As we will see later in the module, dust explosions typically occur via the domino sequence of a primary event (explosion or otherwise) and then a secondary dust explosion. This is consistent with the table shown in the slide, given that the classification of confined explosion (primary scenario) includes dust explosions.

This section examines the fundamentals of dust explosions. We first reintroduce the fire triangle and explosion pentagon, and describe how dusts explode. We then go over dust explosion testing and explosibility parameters, as well as some engineering standards associated with dust explosions.

Play the video embedded in the current slide; you will see an actual dust explosion. The apparatus shown is a device known as the MIKE3, housed in the Dust Explosion Research Laboratory at Dalhousie University. Watch carefully and you will see the formation of a cloud of polyester dust, ignition by electric spark, and subsequent flame propagation.

Dusts can explode. This is a surprising fact to some people but it should not be a surprise to those who handle and process combustible dusts in industry. The slide gives four examples of process incidents to illustrate that dust explosions can and do occur, and that the consequences can be devastating. Unfortunately there are many more dust explosion incident descriptions available in the public domain literature. Other examples are given throughout the module.

Of the incidents shown on the slide, Westray and Imperial Sugar are examined in greater detail in the Case Studies section; West Pharmaceuticals is the subject of one of the exercises in the Evaluation section.

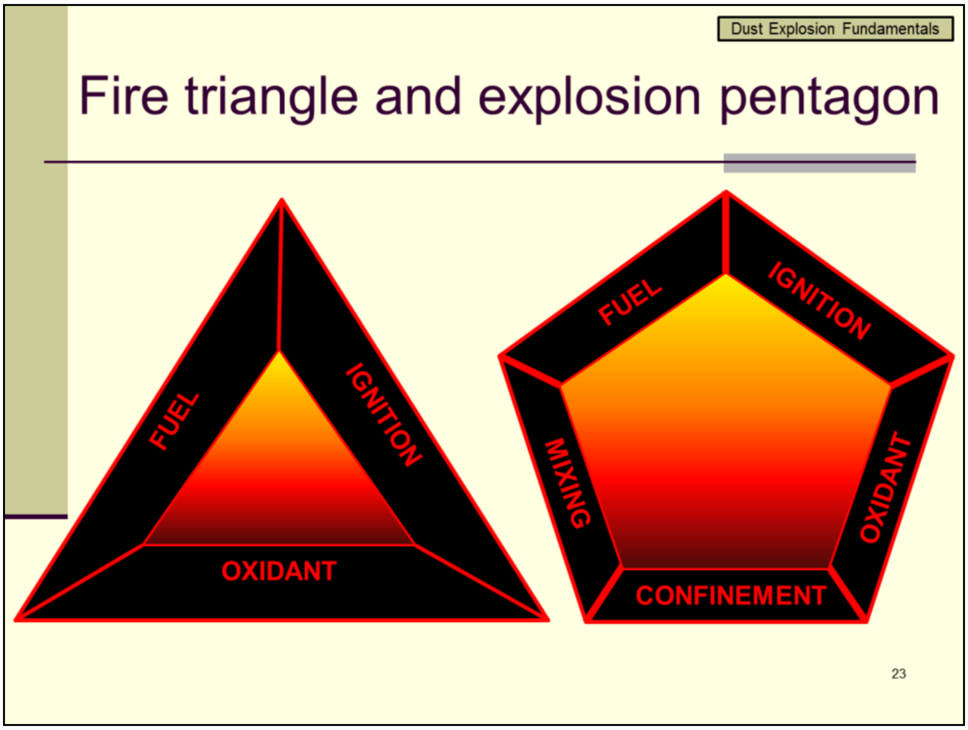
<u>Photographs</u>

Top Left: Richard, K.P., Justice, “The Westray Story – a Predictable Path to Disaster. Report of the Westray Mine Public Inquiry”, Province of Nova Scotia, Halifax, NS (1997).

Top Right: CSB, “Investigation Report. Aluminum Dust Explosion. Hayes Lemmerz International-Huntington, Inc.”, Report No. 2004-01-I-IN, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2005).

Bottom Left: CSB, “Investigation Report. Dust Explosion. West Pharmaceutical Services, Inc.”, Report No. 2003-07-I-NC, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2004).

Bottom Right: CSB, “Investigation Report. Sugar Dust Explosion and Fire. Imperial Sugar Company”, Report No. 2008-05-I-GA, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2009).



Recall the previous discussion concerning the fire triangle and explosion pentagon elements. In a dust fire or explosion, the fuel is of course a solid. It is therefore possible for combustible dust to form layers on equipment and facility surfaces; these layers may burn but they will not explode.

The mixing criterion introduces perhaps the most fundamental difference between gas and dust explosions – again based on the physical state of the fuel. In a dust/air mixture, the dust particles are strongly influenced by gravity; an essential prerequisite for a dust explosion is therefore the formation of a dust/oxidant suspension. An airborne dust cloud will either burn as a flash fire or will explode depending on the degree of confinement.

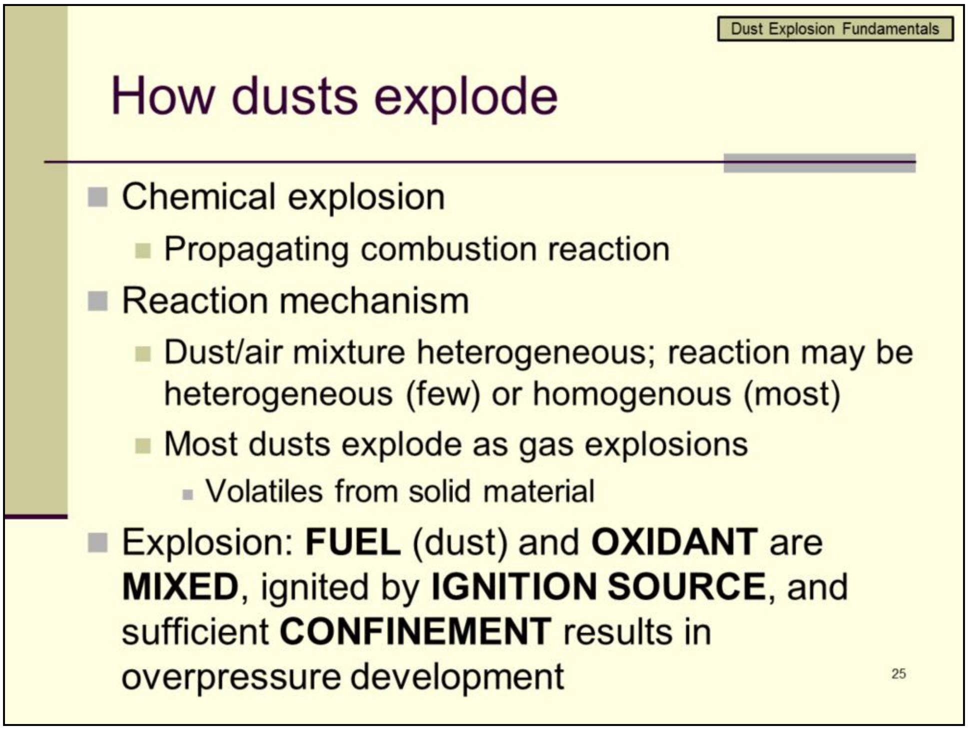
As noted previously, confinement does not need to be complete for a fast-burning flame to transition to an explosion, regardless of fuel type. Partial confinement and turbulence-generating obstacles leading to a high degree of congestion can also be effective in this regard.

Later in the module, we will examine in detail each element of the dust explosion pentagon as well as the special case of dust fires. Before doing that, let’s look at a practical example of the dust explosion pentagon in the next slide.

A hammermill is a process unit used for pulverizing raw material. The slide shows a hammermill (with the cover open) used in a wood-processing facility to accomplish size reduction of sawdust and wood chips (**FUEL**)**.** Magnetic devices are placed on the feed side of the mill to prevent tramp metal from entering (**IGNITION SOURCE**). Inside the hammermill, the pulverizing process produces a cloud (**MIXING**) of wood dust and air (**OXIDANT**). With the cover closed (**CONFINEMENT**), the pentagon is complete.

In spite of all best efforts to remove potential ignition sources, hammermills are prone to experience dust explosions. They are therefore designed and built strong enough to withstand the overpressure originating from such an event inside them.

Photograph: Amyotte, P.R., Pegg, M.J., Khan, F.I., Nifuku, M. and Yingxin, T., “Moderation of Dust Explosions”, Journal of Loss Prevention in the Process Industries, **20**, 675-687 (2007).

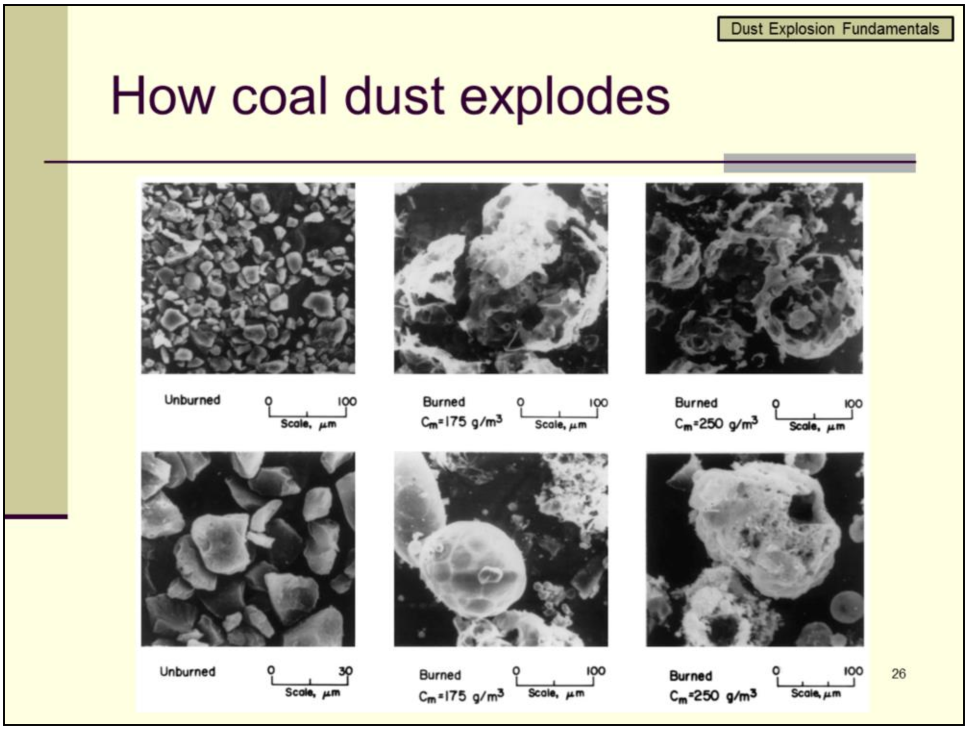


A dust explosion occurs as a result of a chemical reaction (combustion), which is propagated or transmitted spatially through the reaction mass. A dust explosion is therefore a chemical explosion as opposed to a physical explosion.

A dust/air mixture is heterogeneous (two phases). The combustion reaction can be either heterogeneous or homogeneous (one phase). However, only a few dusts undergo heterogeneous combustion, such as the reaction of fine carbon dust with gaseous oxygen.

The vast majority of dust explosion reactions are homogeneous. In these cases, the dust explosion actually occurs as a gas explosion following the generation of volatile matter from the solid dust. Using the example of polyethylene plastic, the plastic would first melt and vapourize, creating a gaseous fuel that would undergo homogeneous combustion with oxygen. This is a step-wise process that may involve the additional complication of a solid, outer oxide layer as in the case of some metals such as aluminum. The next slide shows evidence of this reaction sequence for an organic dust (coal).

Globally – as per the explosion pentagon we have seen previously – the dust and oxidant mix, and the airborne cloud is ignited by an ignition source. Sufficient confinement results in overpressure development from the reaction. The result is an explosion with potentially destructive capabilities.

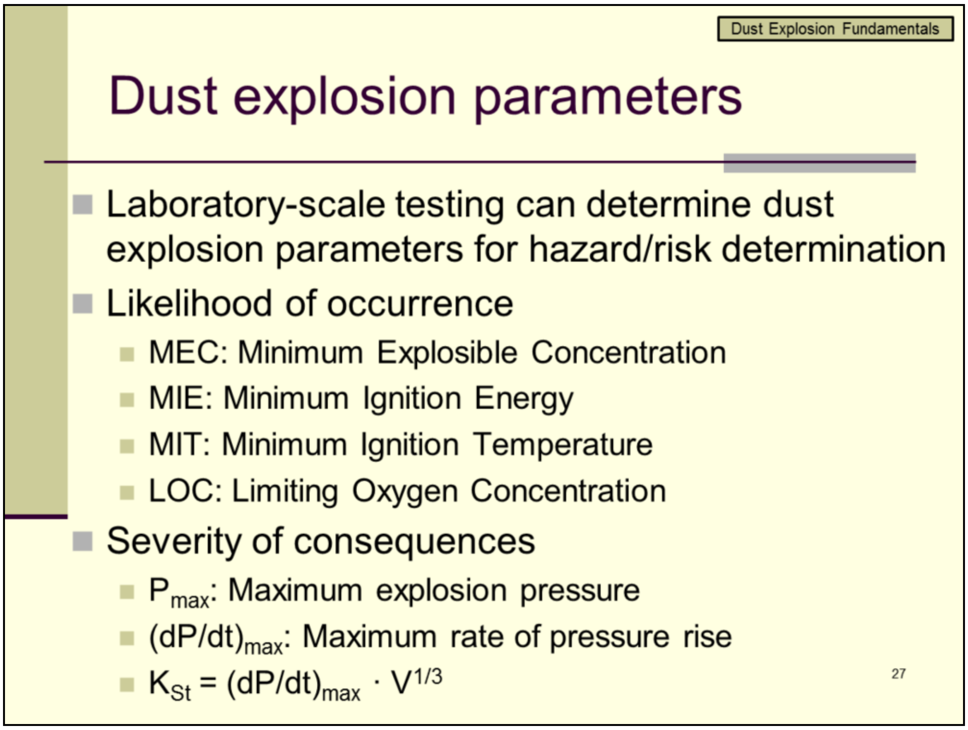


Coal dust explodes in a sequence involving heating to the point of pyrolysis followed by ignition of the evolved volatile matter and subsequent gas-phase flame propagation.

The slide shows scanning electron microscope (SEM) pictures of Pittsburgh seam bituminous coal dust before and after explosion in a laboratory-scale chamber. The burned char residue is seen to consist of rounded particles (or cenospheres), some of which have become fractured or display “blow holes” from which volatiles have been emitted. It is these volatiles that burn in a coal dust explosion leading to increased temperature and pressure in an enclosed volume.

Photograph: Cashdollar, K.L., “Overview of Dust Explosibility Characteristics,” Journal of Loss Prevention in the Process Industries, **13**, 183-199 (2000).

Note that C_m is the dust cloud concentration at the time of explosion.



Text books and data bases can be helpful as indicators of explosibility, but they cannot be seen as a substitute for actual test data on the material being processed. The next slide shows some of the standards and laboratory-scale equipment available for acquiring data for the various explosion parameters shown in the current slide.

Each of these parameters can be categorized according to one of the two components of risk – likelihood of occurrence or severity of consequences. As such, their usefulness lies in developing adequate measures for either the prevention or mitigation of a dust explosion. As we will see in detail later in the module, there are several ways to reduce dust explosion risk once the basic explosibility parameters shown in this slide are known.

Likelihood of Occurrence

MEC, or minimum explosible concentration, is the term used for the LFL, or lower flammability limit, of a dust cloud. Typical units of MEC are g/m^3.

MIE, or minimum ignition energy, is (according to the definition previously given) the minimum electric spark energy that will ignite a dust cloud. Typical units of MIE are °C.

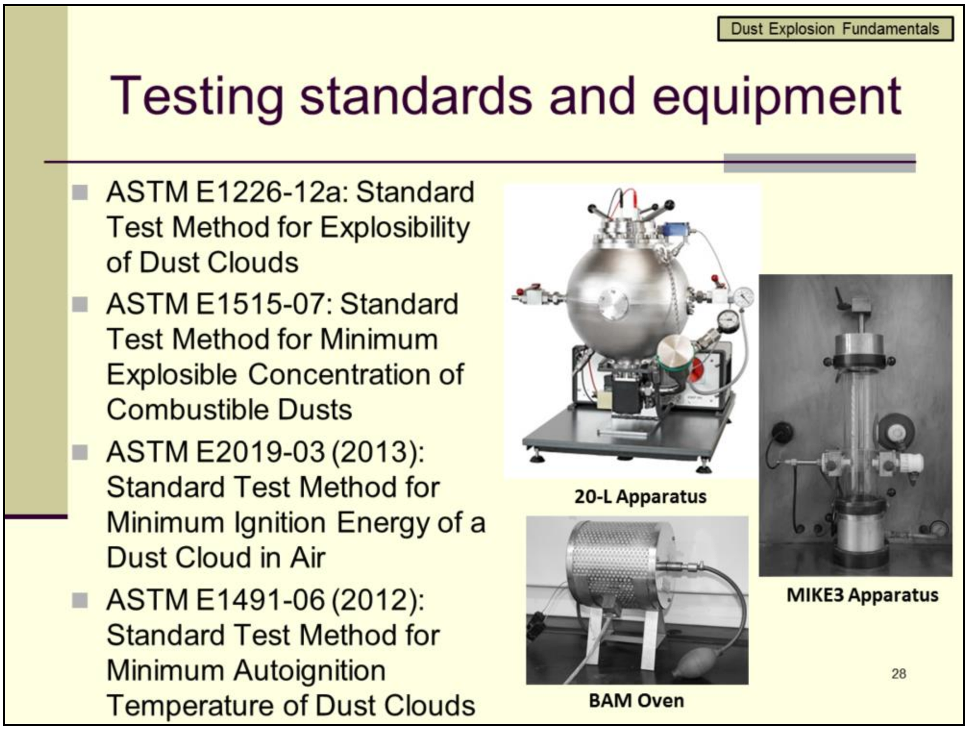
MIT, or minimum ignition temperature, is the term used for the AIT, or autoignition temperature of a dust cloud. (MIT is sometimes called MAIT, or minimum autoignition temperature). Typical units of MIT are °C.

[There is another minimum ignition temperature parameter for dust layers called the LIT, or layer ignition temperature. Typical units of LIT are °C.]

LOC, or limiting oxygen concentration, is the minimum oxygen concentration in the atmosphere required for flame propagation in a dust cloud. Typical units are volume %.

Severity of Consequences

P_{max}, $(dP/dt)_{max}$ and K_{St} are all as previously defined with the previously identified typical units. Note that in K_{St}, the St subscript comes from the first two letters of the German word for dust (*staub*).



This slide shows examples of ASTM International testing standards as well as dust explosion test equipment manufactured by Kuhner AG in Basel, Switzerland. There are other global testing standards and manufacturers of laboratory-scale dust explosion equipment.

P_{max}, $(dP/dt)_{max}$ and K_{St} can be determined according to ASTM E1226 in the 20-L apparatus (or 20-L Siwek chamber, after its designer).

MEC can be determined according to ASTM E1515 in the 20-L apparatus.

MIE can be determined according to ASTM E2019 in the MIKE3 apparatus.

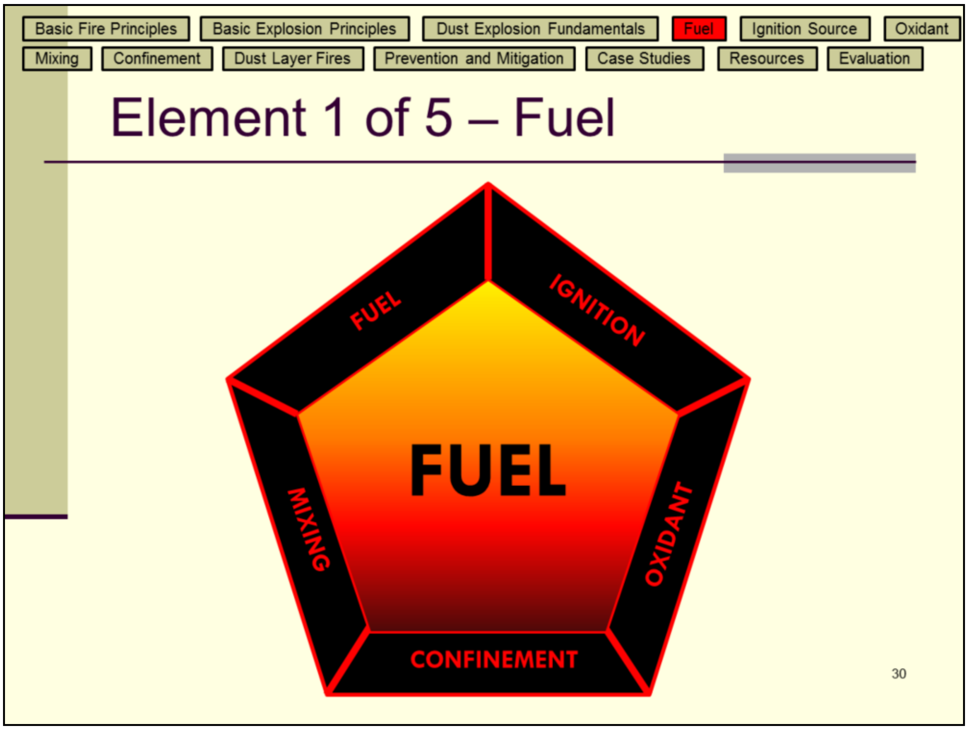
MIT can be determined according to ASTM E1491 in the BAM oven.

As indicated in the Resources section of the module, these and other testing standards are available on the ASTM International web site.

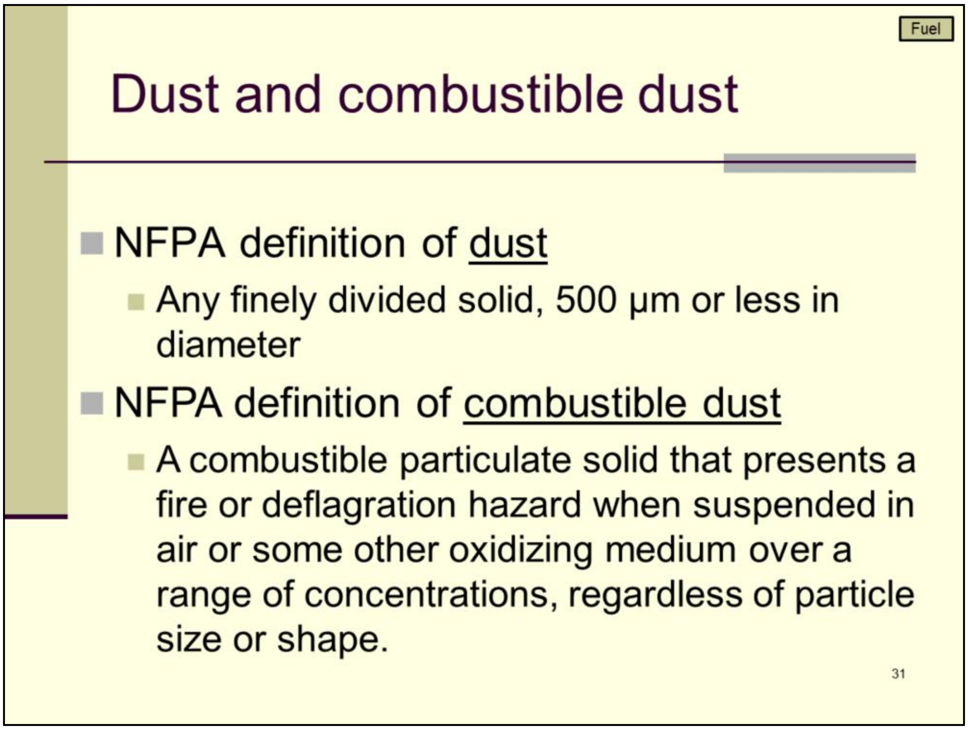
The National Fire Protection Association (United States) has published several standards relating to the prevention and mitigation of dust explosions:
NFPA 61 – Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities
NFPA 68 – Standard on Explosion Protection by Deflagration Venting
NFPA 69 – Standard on Explosion Prevention Systems
NFPA 120 – Standard for Fire Prevention and Control in Coal Mines
NFPA 484 – Standard for Combustible Metals
NFPA 499 – Recommended Practice for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas
NFPA 654 – Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids
NFPA 664 – Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities

As indicated in the Resources section of the module, these and other risk control standards are available on the NFPA web site.

Similar to the testing standards listed on the previous slide, there are other global risk control standards. Examples include the European (EN) Standards and the VDI Guidelines in Germany. The Health and Safety Executive or HSE (United Kingdom) web site (www.hse.gov.uk) gives a good overview of two European Directives for controlling explosive atmospheres – ATEX 95 (ATEX Equipment Directive) and ATEX 137 (ATEX Workplace Directive).



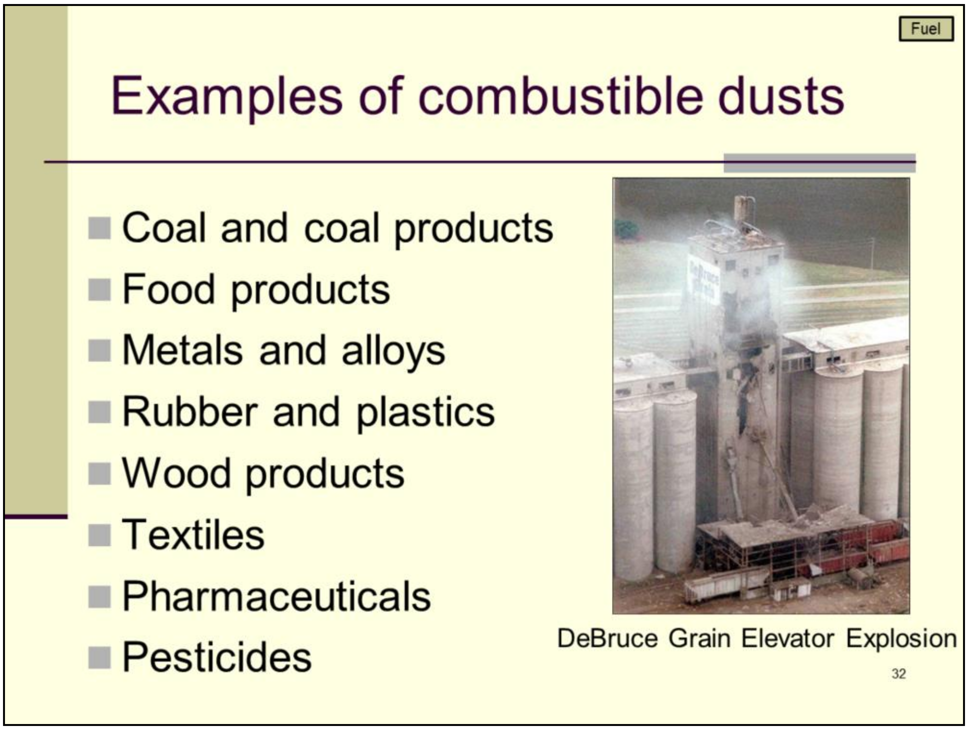
This section covers dust as a fuel source. Combustible dust is defined, including conditions of particle size and shape, and examples of combustible dusts and typical process units that experience dust explosions are given. Dust layers and airborne concentrations arising from layers are described. Finally, the unique fuel system known as a hybrid mixture is examined.



The NFPA distinguishes between a dust and a combustible dust. By these definitions, not all dusts are combustible dusts and not all combustible dusts are dusts!

Confusing? A bit perhaps, but the takeaway lesson here is that the important definition for our purposes is **combustible dust**. Throughout this module, whenever the word dust is used, it should be taken to mean a combustible dust as per the above NFPA definition.

One should not view a defined boundary of 500 μm as a sharp delineation between dusts that are explosible and those that are non-explosible. What determines whether a given particulate material represents a dust explosion hazard is its actual chemical composition in addition to physical parameters such as particle size and particle shape.

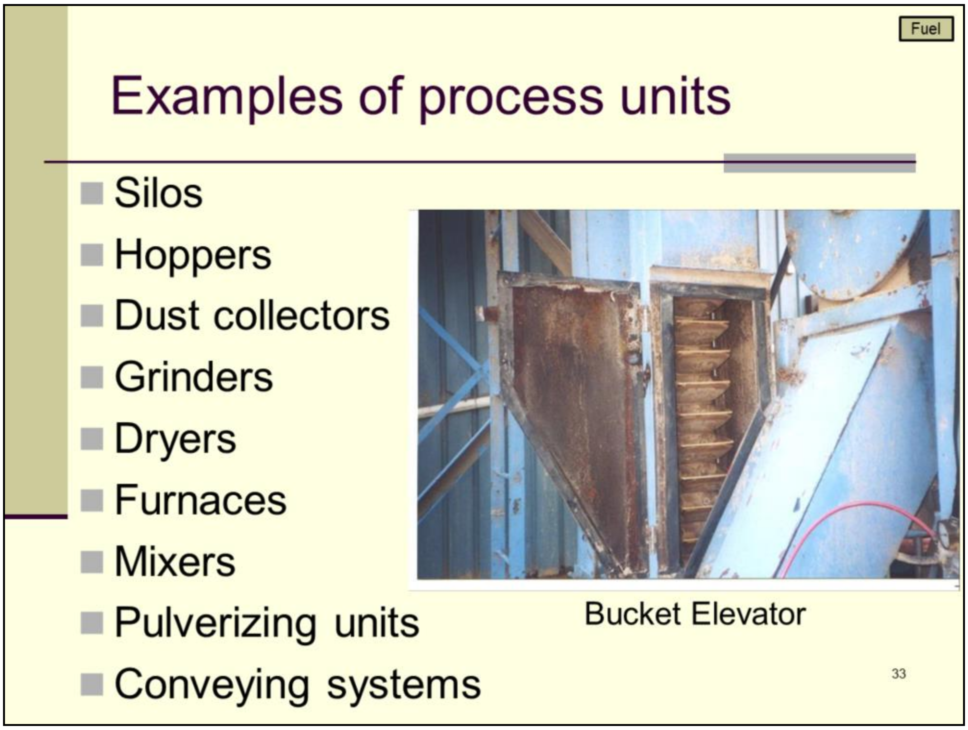


Combustible dusts can be found across many industries. The following is a list of just some of the many types of combustible dusts: coal and coal products such as activated carbon, bituminous coal and pulverized coal; food products such as grain dust, flour, sugar, coffee and dextrose; metals and alloys such as aluminum, bronze, silicon, zinc and titanium; rubber, plastics, polymer and resins; wood and paper; cotton and wool; pharmaceuticals; pesticides.

Because dust explosions arise from the reaction of a fuel with oxygen to generate oxides and heat, they cannot occur with materials that are already stable oxides (such as silicates and carbonates).

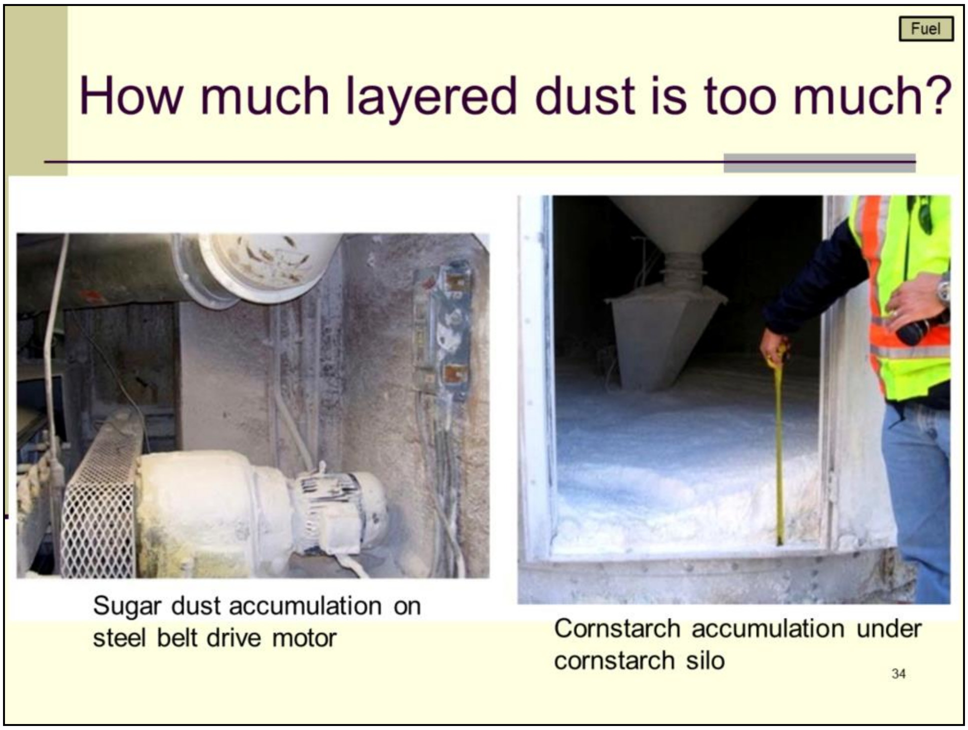
References for this slide and further examples can be found in: Amyotte, P., “An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace”, Elsevier/Butterworth-Heinemann, Waltham, MA (2013).

Photograph: Kauffman, C.W., “The DeBruce Grain Elevator Explosion”, Proceedings of the Seventh International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions, Volume III, St. Petersburg, Russia (July 7-11, 2008), pp. 3-26.



The previous list of combustible dusts largely defines the industrial plant in which dust explosions are most commonly experienced. Examples of process units that have been subject to the dust explosion problem are given in this slide. Dust collectors are arguably the most at risk in this regard.

References for this slide and further examples can be found in: Amyotte, P., “An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace”, Elsevier/Butterworth-Heinemann, Waltham, MA (2013).



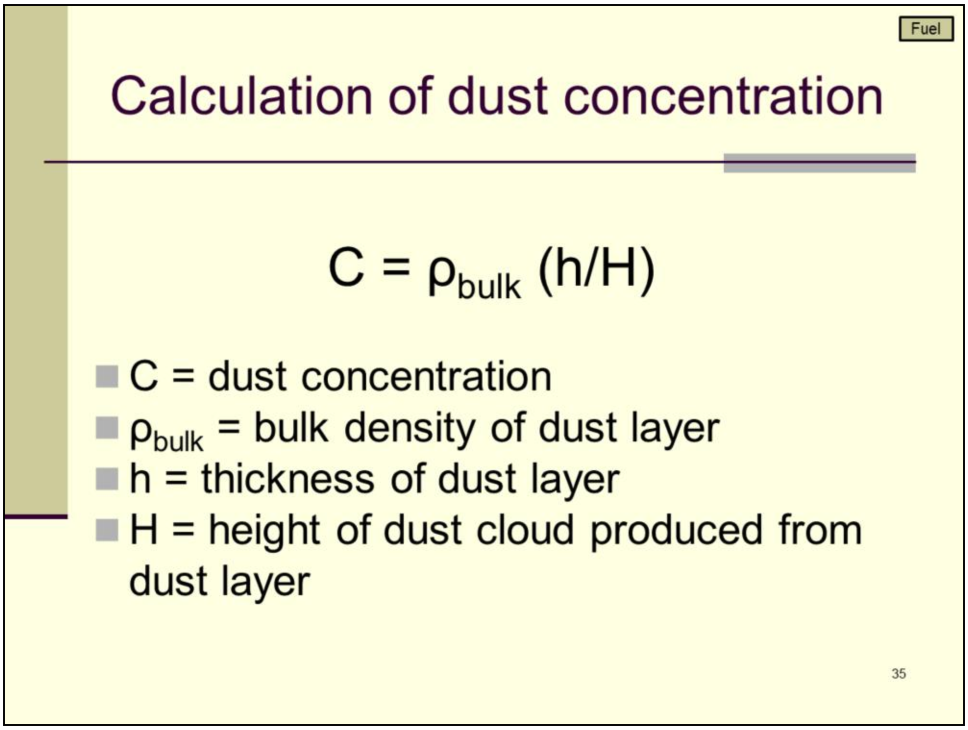
Dust explosions occur either inside process vessels in which a dust cloud already exists, or as a result of a dust cloud formed by dispersion of a dust layer. (These mechanisms are treated in more detail later in the module.)

For the latter case, how thick a dust layer is needed to support a dust explosion if the layer forms an airborne cloud? The answer is not very thick – typically on the order of a millimeter or so.

In general, there is too much layered dust if it creates an opaque layer over the surface; for example – if you can't tell the colour of the surface beneath the layer. Or, there is too much layered dust if you can leave visible markings in the dust, such as leaving footprints or being able to write your initials or "clean me" in the dust.

The slide gives two examples of dust layers. The photograph on the right shows a significant spill, which would easily be considered "too much". The photograph on the left shows a much thinner dust layer, but it too would be considered "too much".

Photographs: CSB, "Investigation Report. Sugar Dust Explosion and Fire. Imperial Sugar Company", Report No. 2008-05-I-GA, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2009).

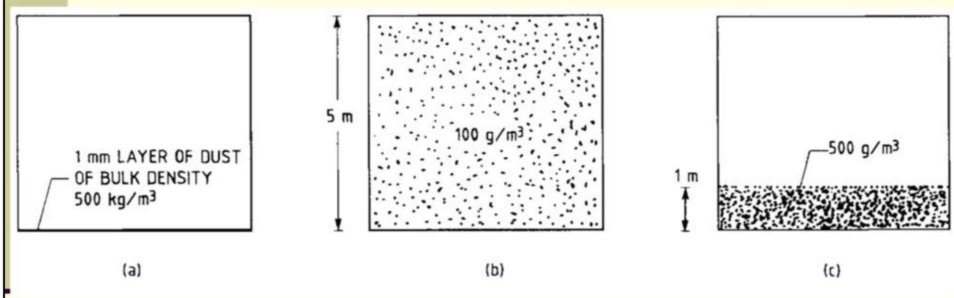


The concentration of a dust cloud resulting from dispersion of a dust layer in air can be determined by the equation shown in the slide. This is an estimate that assumes complete, uniform dust dispersion. Nevertheless, this simple expression is helpful in demonstrating that very thin layers of combustible dust can be hazardous. An example of the use of this equation is given in the next slide.

Equation Source: Eckhoff, R.K., “Dust Explosions in the Process Industries”, 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).

Fuel

Example: $C = \rho_{bulk} (h/H)$



$h = 1$ mm
$\rho_{bulk} = 500$ kg/m^3

$H = 5$ m
$C = 100$ g/m^3

$H = 1$ m
$C = 500$ g/m^3

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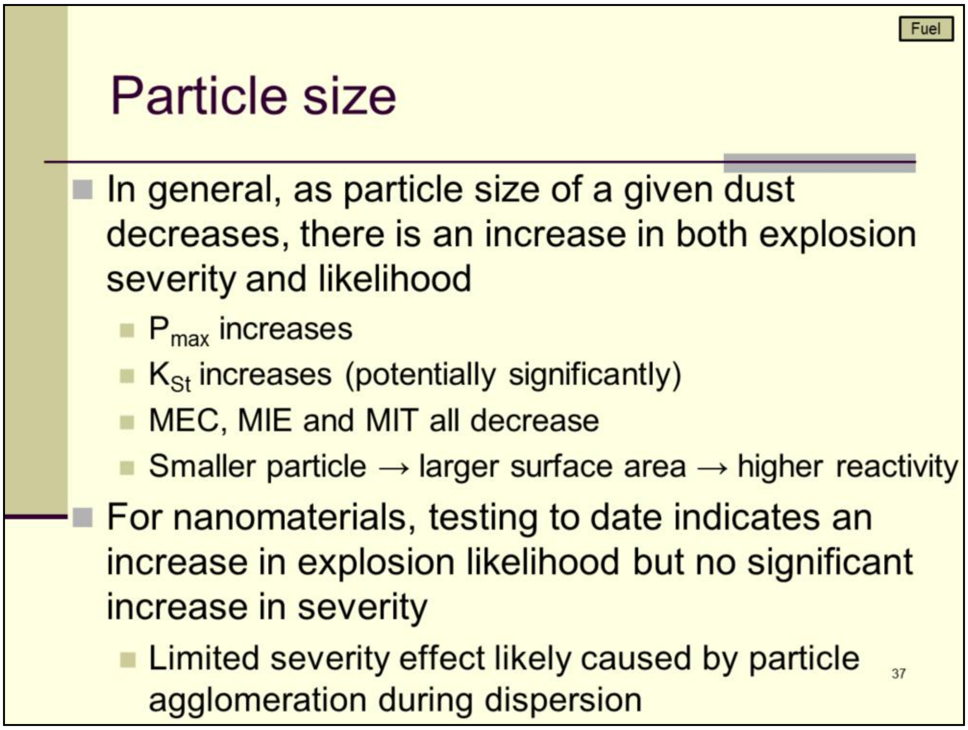
The figure in the slide shows two scenarios for a given dust layer thickness (1 mm) and bulk density (500 kg/m^3).

With uniform dispersion throughout a 5-m high enclosure, the resulting dust cloud will have an average concentration of 100 g/m^3. Such a concentration is of the order of the minimum amount required to initiate an explosion – i.e., the MEC – for many dusts.

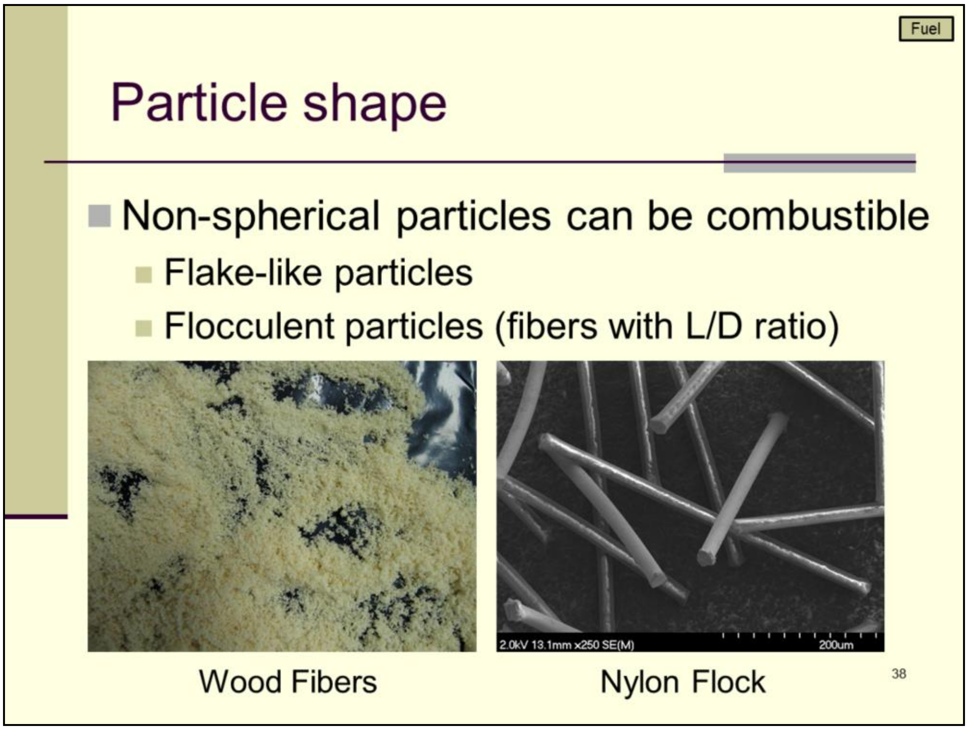
With only partial dispersion up to 1 m above the enclosure floor, the resulting dust cloud will have an average concentration of 500 g/m^3. Such a concentration is of the order of the optimum concentration – i.e., the concentration producing the most destructive overpressures and rates of pressure rise – for many dusts.

Figure: Eckhoff, R.K., "Dust Explosions in the Process Industries", 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).



The particle size of a given combustible dust has a significant influence on its explosibility. In general, a decrease in particle size has been shown to increase the likelihood of occurrence of a dust explosion as well as its consequence severity. P_{max} increases. $(dP/dt)_{max}$ and hence K_{St} also increase; this increase can potentially be substantial. MEC, MIE and MIT all decrease with decreasing particle size. This is due to surface area effects – a smaller particle means a larger surface area and therefore enhanced reactivity. The fine particles (typically < 75 μm) in a wide particle size distribution make the greatest contribution to dust reactivity and explosibility.

One exception to this general behaviour is nanomaterials. Although only limited test results are currently available, as particle size decreases into the nano-range, there appears to be no significant increase in explosion severity – yet explosion likelihood can increase dramatically. Nanomaterials are extremely sensitive, and may self-ignite under certain testing and handling conditions. Agglomeration of primary nanoparticles into micron-size aggregates during dust dispersion is thought to be responsible for the limited increase in P_{max} and K_{St}.

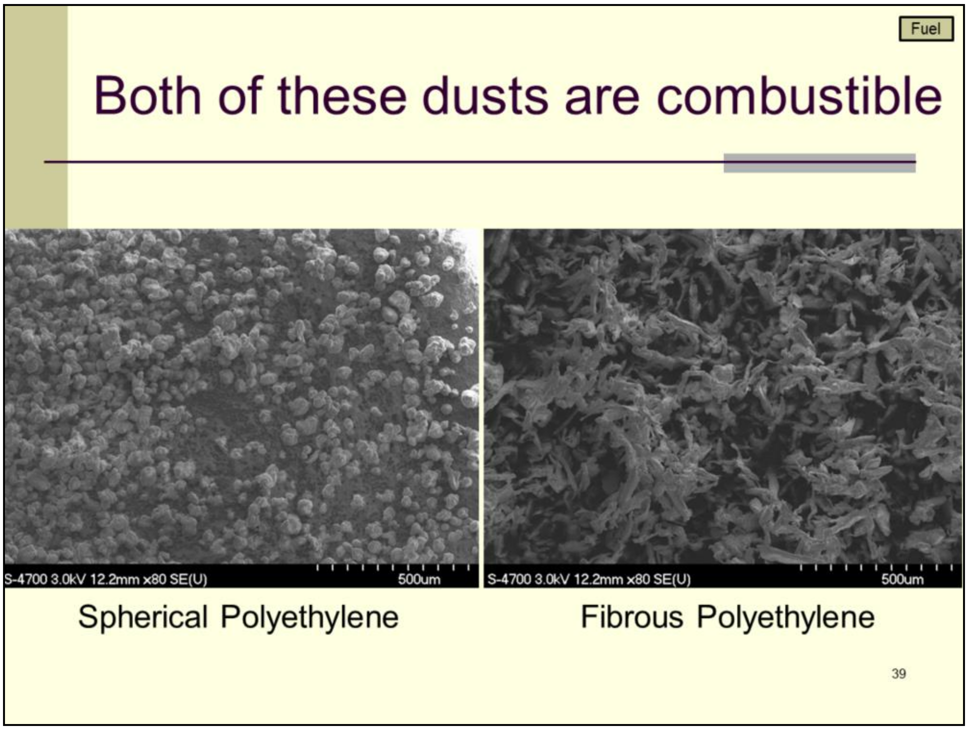


Dust particles do not need to be spherical or near-spherical to be combustible. Flake-like particles and flocculent materials (fibrous materials better characterized by a length-to-diameter ratio than a particle diameter) can also pose an explosion hazard.

The slide gives two photographs. The one on the left (taken with a normal digital camera) shows combustible wood fibers. The SEM image on the right shows combustible nylon (polyamide 6.6) flock.

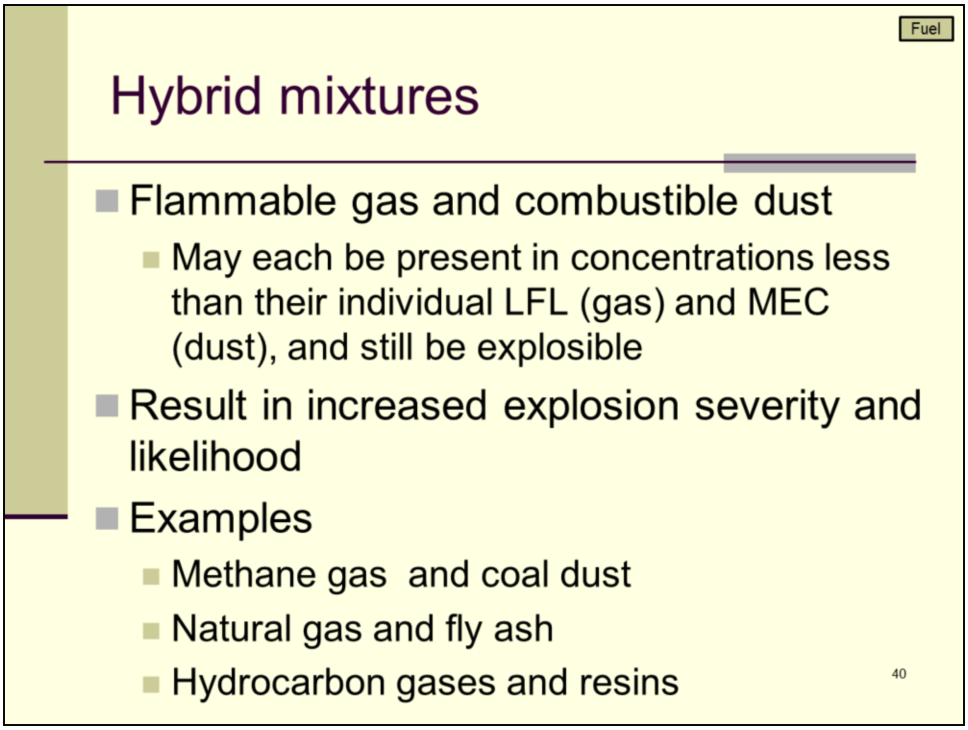
Photograph (Left): Amyotte, P.R., Cloney, C.T., Khan, F.I. and Ripley, R.C., “Dust Explosion Risk Moderation for Flocculent Dusts”, Journal of Loss Prevention in the Process Industries, **25**, 862-869 (2012).

Photograph (Right): Iarossi, I., Amyotte, P.R., Khan, F.I., Marmo, L., Dastidar, A.G. and Eckhoff, R.K., “Explosibility of Polyamide and Polyester Fibers”, Journal of Loss Prevention in the Process Industries, **26**, 1627-1633 (2013).



Each of the spherical and fibrous polyethylene samples shown in the SEMs on this slide pass through a 200-mesh sieve, and are therefore nominally < 75 µm in size. Explosion testing for these samples determined that each was capable of generating overpressures of approximately 7 bar(g) – i.e., seven times atmospheric pressure – and rates of pressure rise as high as 300 – 400 bar/s in a volume of 20 L.

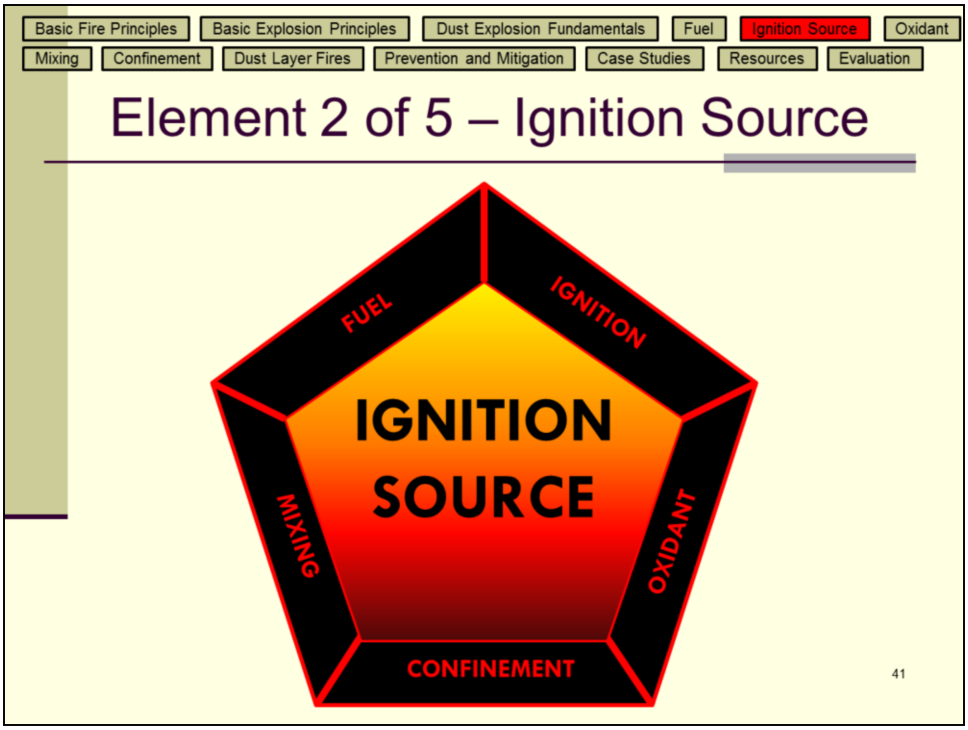
Photographs: Amyotte, P.R., Cloney, C.T., Khan, F.I. and Ripley, R.C., “Dust Explosion Risk Moderation for Flocculent Dusts”, Journal of Loss Prevention in the Process Industries, **25**, 862-869 (2012).



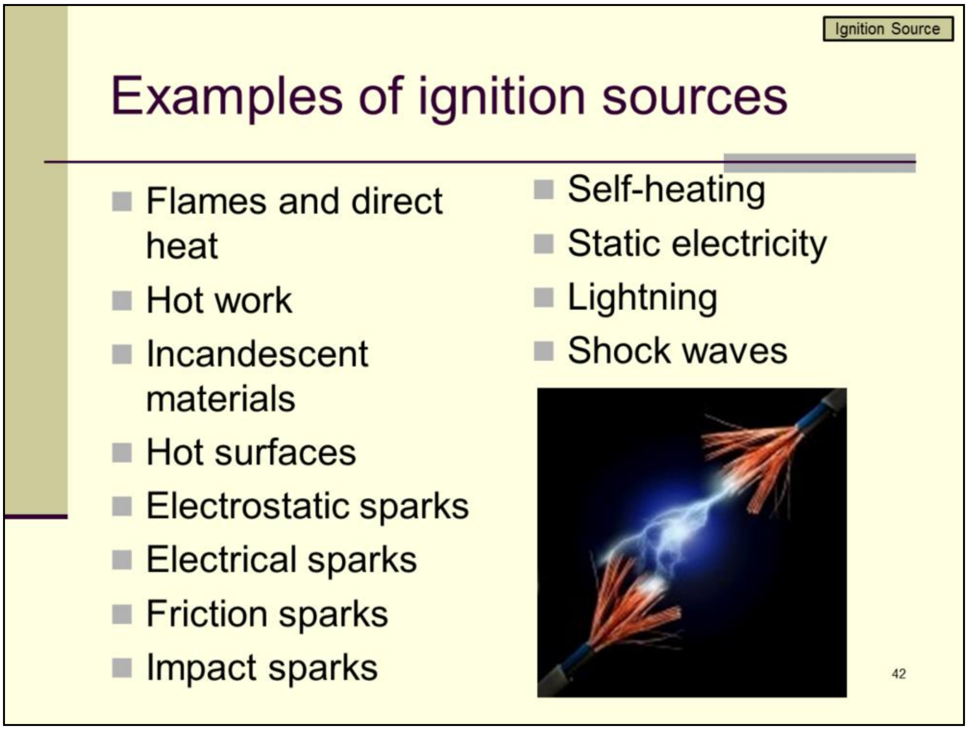
A hybrid mixture explosion can occur as a result of the mixing of a flammable gas and a combustible dust. The gas concentration may be less than its lower flammability limit (LFL) and/or the dust concentration may be less than its minimum explosible concentration (MEC), and yet the mixture can still be explosible. The focus when discussing hybrid mixtures is often on admixture of a flammable gas in concentrations below the LFL of the gas itself, to an already explosible concentration of dust.

In a hybrid mixture explosion, there would be higher values of P_{max} and $(dP/dt)_{max}$, and lower values of MEC and MIE (with respect to the dust alone), which results in an increase in both explosion severity and likelihood of occurrence.

A well-known example of a hybrid mixture is methane gas and coal dust in an underground coal mine. Other examples include natural gas and fly ash in fossil-fuel power plants, and gaseous hydrocarbons and resins in plastic powder production facilities.



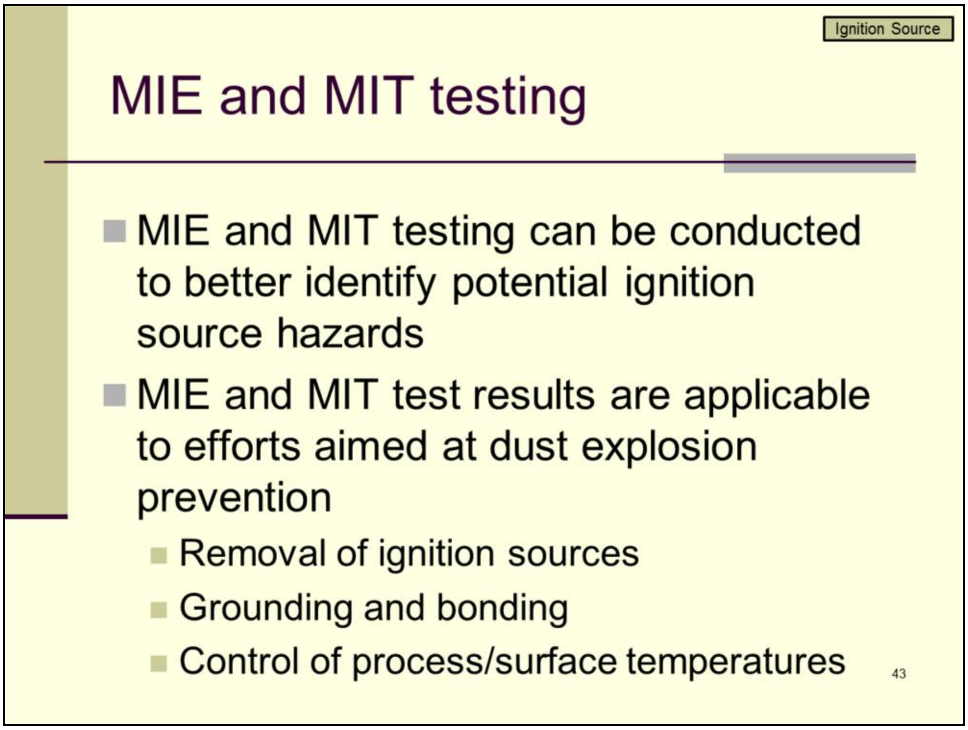
This section deals with possible dust explosion ignition sources, as well as introducing minimum ignition energy and minimum explosion temperature testing and results. The relationship between gas and dust MIE values is also described.



Dust explosion triggers include the following:

- flames and direct heat,
- hot work (e.g., welding and cutting),
- incandescent material (e.g., smoldering particles),
- hot surfaces, (e.g., overheated bearings),
- electrostatic sparks (caused by electrostatic discharge from electrical equipment),
- electrical sparks (such as may be caused by switching operations),
- friction sparks and hot spots (caused by rubbing between solids and friction-induced heating, respectively),
- impact sparks (ignition by surface heating resulting from metal-on-metal impact),
- self-heating (spontaneous combustion),
- static electricity (electrostatic sparks caused by process operations such as pouring and size reduction),
- lightning, and
- shock waves.

Reference: Abbasi, T. and Abbasi, S.A., “Dust Explosions – Cases, Causes, Consequences, and Control”, Journal of Hazardous Materials, **140**, 7-44 (2007).



Many ignition sources involve either an energetic spark or a hot-surface temperature. To better identify potential ignition source hazards in terms of both energy and temperature requirements, minimum ignition energy and minimum ignition temperature testing of a given dust can be conducted.

Test results can be implemented in applications such as removal of ignition sources, grounding and bonding as a form of protection against static electricity build-up and electrostatic discharges, and control of process and surface temperatures.

Ignition Source

MIE values of some dusts

Material	MIE with inductance [mJ]	MIE without inductance [mJ]
Epoxy coating powder	1.7	2.5
Polyester coating powder	2.9	15
Polyamide coating powder	4	19
Magnesium granulate	25	200
Flock	69-98	1300-1600

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Decades ago, it was believed that all dusts had MIEs greater than 10 mJ. As testing methods were improved, it was discovered that many dusts had much lower MIEs, in the range of 1 mJ or less. The table in the slide shows MIE values for different particulate materials.

MIE is tested both with and without inductance in the spark circuitry. It has been found that the use of inductance usually lowers the MIE, and sometimes the reduction is quite significant as we can see in this table. This is because the use of inductance results in a longer spark duration (i.e., protracted spark), and therefore a higher probability of ignition.

Note: These values, although typical for their dust types are not specific to all similar dusts. A dust source must be tested in order to obtain specific values. Additionally, although particle size is not given for these examples, we know from previous discussion in this module that particle size does have an effect on MIE.

Table adapted from: von Pidoll, U., “The Ignition of Clouds of Sprays, Powders and Fibers by Flames and Electric Sparks”, Journal of Loss Prevention in the Process Industries, **15**, 305-310 (2002).

Ignition Source

Ignition of titanium dust

Size	MIE [mJ]		MIT [°C]
	With inductance	Without inductance	
<150 µm	10-30	1-3	>590
<45 µm	1-3	1-3	460
≤20 µm	<1	<1	460
150 nm	Not determined	<1	250
60-80 nm	Not determined	<1	240
40-60 nm	Not determined	<1	250

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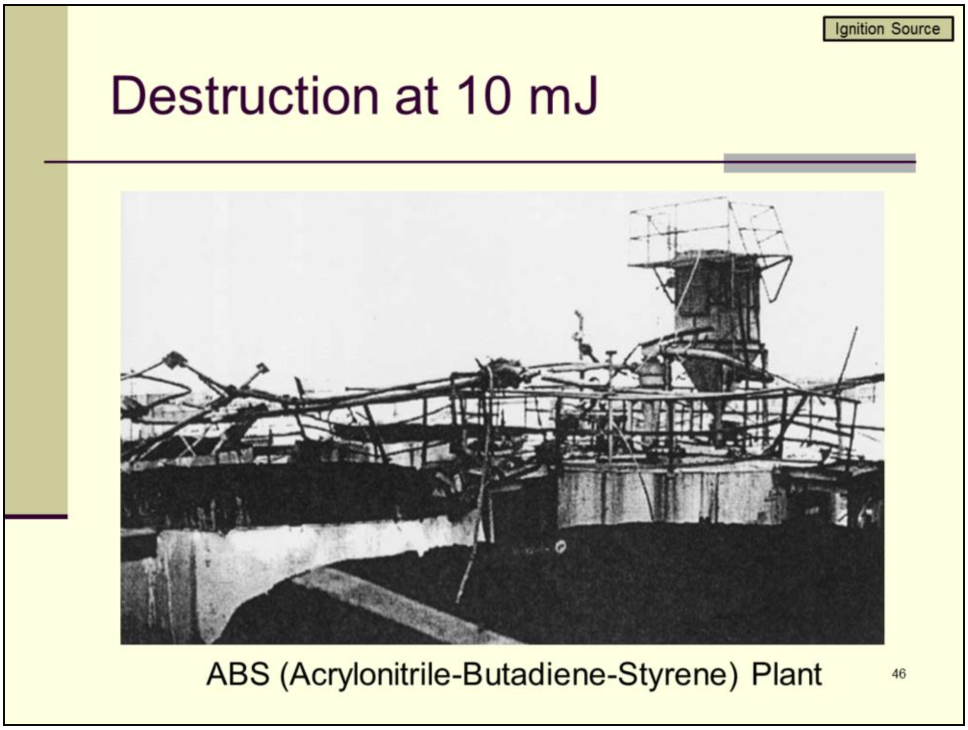
Nano-size metals such as aluminum and titanium have been shown to have very low ignition energies of less than 1 mJ, which is the lower testing limit of the MIKE3 apparatus (shown in a previous slide).

In this table we see these low MIE results for nano-titanium. We also see that even the micron-size dusts have low MIE values. And we also see the decrease in minimum ignition temperature (MIT) from micron- to nano-size titanium.

Table adapted from: Boilard, S.P., Amyotte, P.R., Khan, F.I., Dastidar, A.G. and Eckhoff, R.K., “Explosibility of Micron- and Nano-Size Titanium Powders”, Journal of Loss Prevention in the Process Industries, **26**, 1646-1654 (2013).



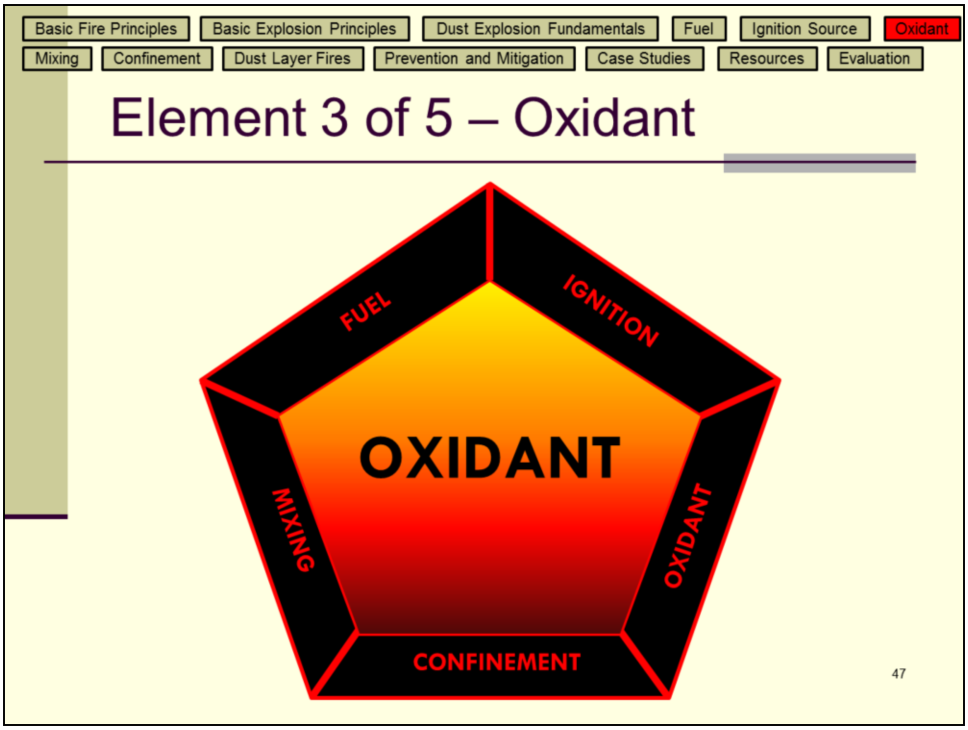
Flammable gases typically have lower ignition energies than combustible dusts. For example, the CSB report on the Hoeganaes incidents presented in the later module section on Case Studies gives an MIE of 0.02 mJ for hydrogen and > 500 mJ for the iron dust involved in the actual incidents.
(CSB, “Case Study. Hoeganaes Corporation: Gallatin, TN. Metal Dust Flash Fires and Hydrogen Explosion”, No. 2011-4-I-TN, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2011).)

But don’t be fooled into thinking that the relatively higher MIEs of combustible dusts mean that dust explosions – once initiated – are not potentially devastating. The figure in this slide indicates otherwise. (Figure: Kao C.-S. and Duh, Y.-S., “Accident Investigation of an ABS Plant”, Journal of Loss Prevention in the Process Industries, **15**, 223-232 (2002).)

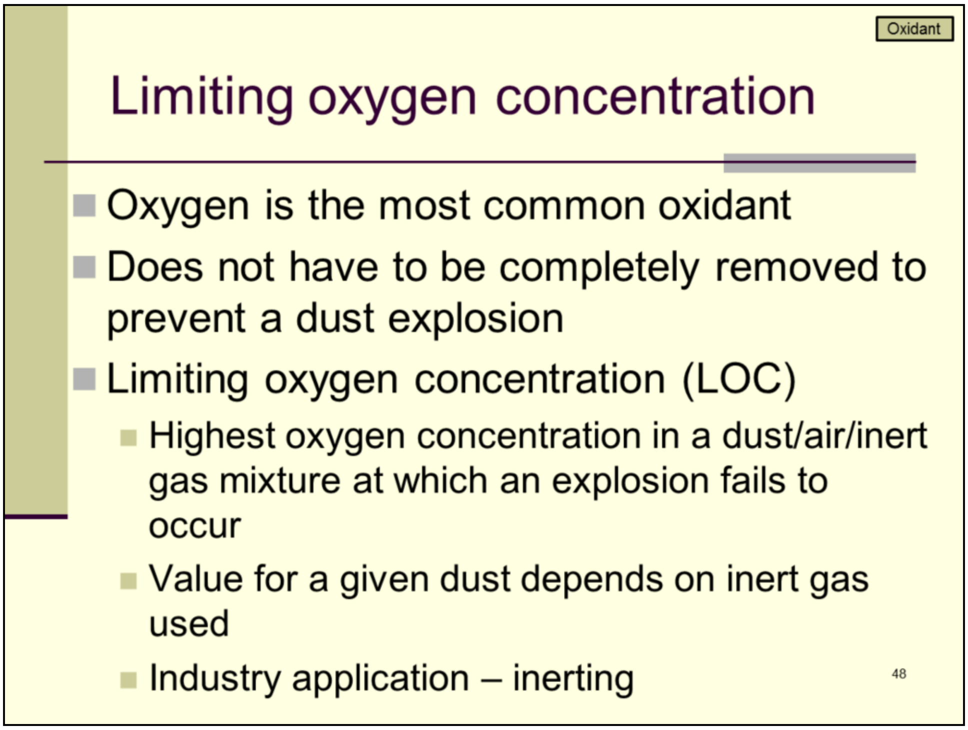
Kao and Duh (2002) describe a series of dust explosions in the silo area of an ABS (acrylonitrile-butadiene-styrene) plant; the participating materials were ABS (which is a rubber-containing plastic) and SAN (polystyrene-acrylonitrile). Several silos were affected, with the top-plate and bag-filter (dust collector) for each being destroyed. An indication of the plant damage is given by the figure in this slide.

The incident investigation team eventually concluded that the explosion was initiated in one of the silos undergoing gravitational filling of ABS powder, with flame propagation to the other involved silos occurring through interconnecting pipes. The most likely ignition scenario in the first silo was thought to be a bulked brush (conical pile or cone) discharge between the compacted powder and the grounded silo wall. Such discharges are relatively intense and have energies up to several hundred mJ. The MIE of the ABS powder was measured as **10 mJ**.

Additional original source material can be found in: Amyotte, P., “An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace”, Elsevier/Butterworth-Heinemann, Waltham, MA (2013).



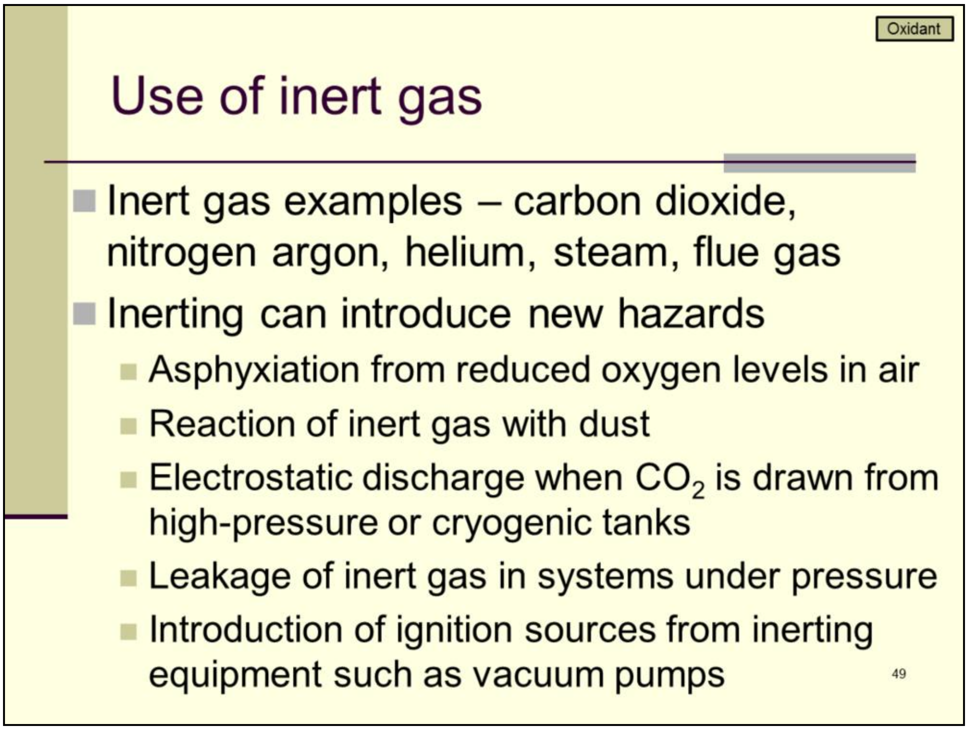
This section examines two aspects related to oxygen as the most common oxidant for combustion: (i) the concept of the limiting oxygen concentration, or LOC, and (ii) the use of inert gases as an explosion prevention technique. LOC is defined and representative values are given. Various candidate inert gases are identified and their effect on key explosion parameters is illustrated.



Oxygen is the most common oxidant found in industry. Air is typically comprised of 21 % by volume of oxygen.

While an oxidant must be present for combustion to occur, its removal does not need to be complete to prevent the occurrence of a dust explosion. The limiting oxygen concentration (LOC) is defined as the highest oxygen concentration at which an explosion fails to occur in a given dust/air/inert gas mixture.

The inert gas used for this purpose affects the measured value of LOC; the effectiveness of different inert gases is shown in a later slide. LOC data can be applied in industry to a prevention technique known as inerting (in which a process is operated under a blanket of inert gas). However, inerting may not always be feasible, and there can be hazards other than explosions associated with inerting. Some of these hazards are shown in the following slide.



Candidate inert gases include: carbon dioxide, nitrogen, argon, helium, steam and flue gas.

Inerting can greatly reduce the risk of a dust explosion. In the act of removing one hazard, however, new hazards may be introduced as shown by the list given in the slide. Asphyxiation is a key and insidious hazard; safe oxygen levels for human beings are between 19.5 and 23.5 volume %. Carbon dioxide has been known to react with aluminum dust, and nitrogen with magnesium dust at high temperatures.

References for this slide and further examples can be found in: Amyotte, P., “An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace”, Elsevier/Butterworth-Heinemann, Waltham, MA (2013).

Oxidant

LOC values of some dusts

Material	LOC with nitrogen [volume %]
Pea flour	15.5
Calcium stearate	12.0
Wheat flour	11.0
High-density polyethylene	10.0
Sulfur	7.0
Aluminum	5.0

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In this table we see representative values of LOC for various materials. Aluminum dust is highly reactive and therefore has a low LOC.

In industry – to account for operating errors and upset conditions – a safety factor is normally applied to the measured LOC (e.g., the LOC percentage minus a further set percentage such as 2 volume %).

Note: These values, although typical for their dust types are not specific to all similar dusts. A dust source must be tested in order to obtain specific values. Additionally, although particle size is not given for these examples, it should not come as a surprise that particle size has an effect on LOC.

Table and text adapted from: Hoppe, T. and Jaeger, N., “Reliable and Effective Inerting Methods to Prevent Explosions”, Process Safety Progress, **24**, 266-272 (2005).

Oxidant

Inert gas effectiveness

Magnesium Dust

Inert Gas	LOC [volume %]
Nitrogen (diatomic)	6.8
Carbon dioxide (triatomic)	5.5
Argon (monatomic)	4.0

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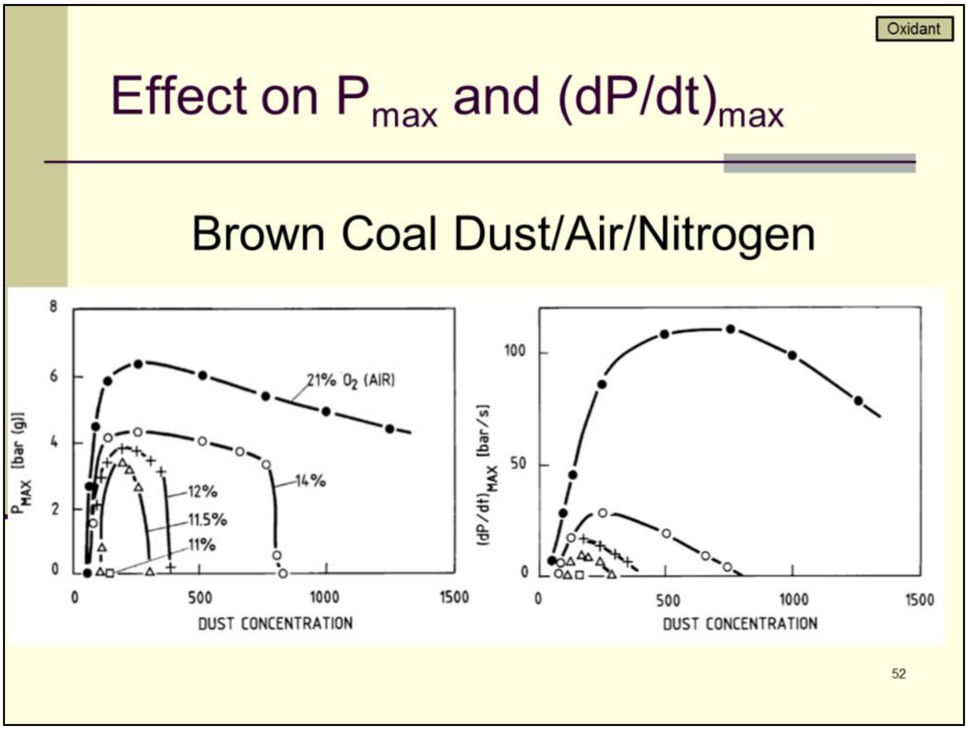
Inert gases have different degrees of effectiveness. This table shows the LOC values for three different inert gases with a specific sample of magnesium dust. Gases with multiatomic molecules have a greater capacity for energy absorption, and hence would be more effective at inerting than monatomic gases, resulting in a higher LOC value. This is why argon (monatomic) has the lowest LOC of the three gases shown.

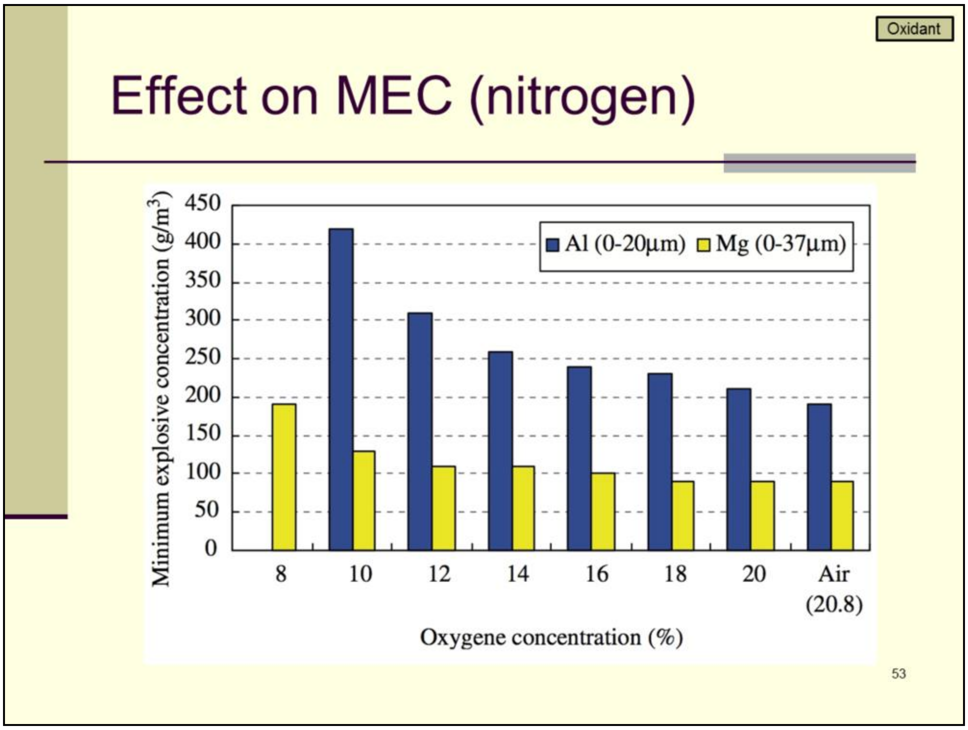
Table adapted from: Li, G., Yuan, C.M., Fu, Y., Zhong, Y.P. and Chen, B.Z., “Inerting of Magnesium Dust Coud with Ar, N_2 and CO_2”, Journal of Hazardous Materials, **170**, 180-183 (2009).



This figure shows the inerting effectiveness of nitrogen on the maximum explosion pressure and maximum rate of pressure rise of a sample of brown coal.

It can be seen that the limiting oxygen concentration (LOC) was 11 volume %, as an explosion was no longer possible at this level (zero values of overpressure and rate of pressure rise). We can also see that there was a steady reduction in overpressure and rate of pressure rise as the oxygen concentration was reduced below 21 volume %, until the limiting oxygen concentration was reached.

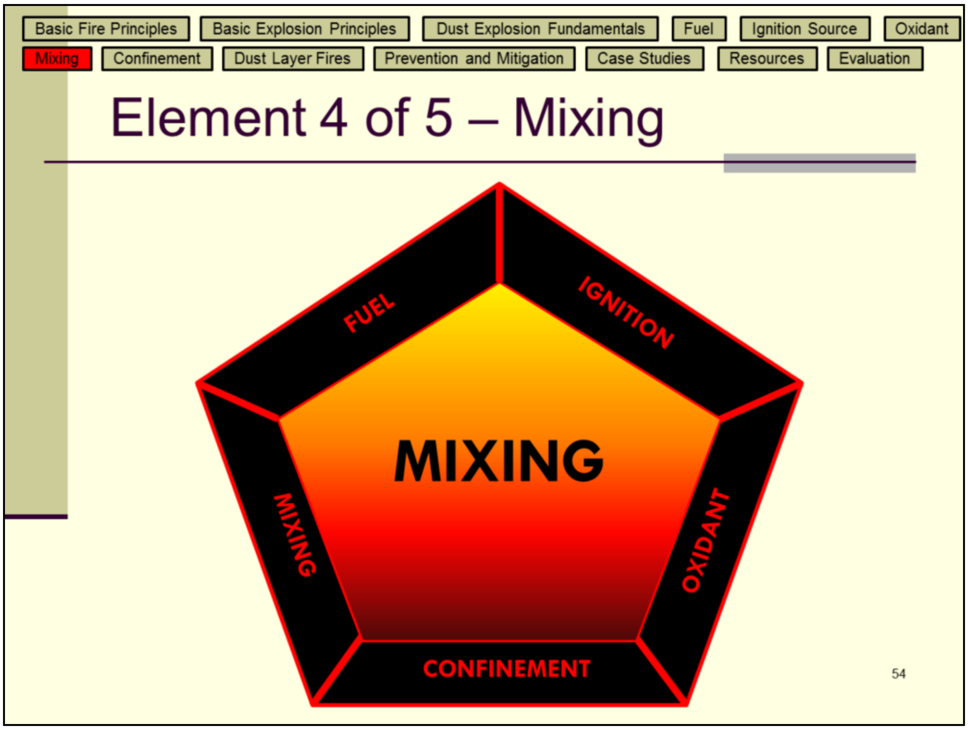
Figure: Eckhoff, R.K., “Dust Explosions in the Process Industries”, 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).
Original Source: Wiemann W., “Influence of Temperature and Pressure on the Explosion Characteristics of Dust/Air and Dust/Air/Inert Gas Mixtures”, In: Cashdollar K.L. and Hertzberg M. (Editors), “Industrial Dust Explosions. ASTM Special Technical Publication 958”, American Society for Testing and Materials, Philadelphia, PA (1987).



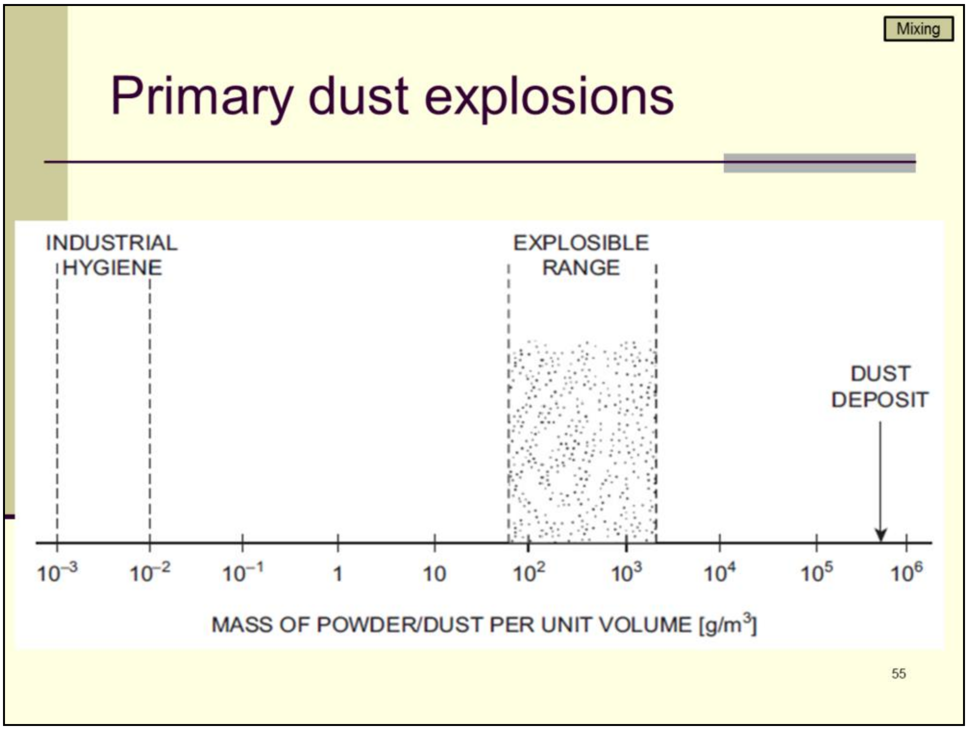
This figure shows the inerting effectiveness of nitrogen on the minimum explosible concentration of samples of aluminum and magnesium.

It is clear that the trend with oxygen level reduction is toward a limiting oxygen concentration at which explosions are no longer possible.

Figure: Nifuku, M., Koyanaka, S., Ohya, H., Barre, C., Hatori, M., Fujiwara, S., Horiguchi, S. and Sochet, I., “Ignitability Characteristics of Aluminum and Magnesium Dusts that are Generated During the Shredding of Post-Consumer Wastes”, Journal of Loss Prevention in the Process Industries, **20**, 322-329 (2007).



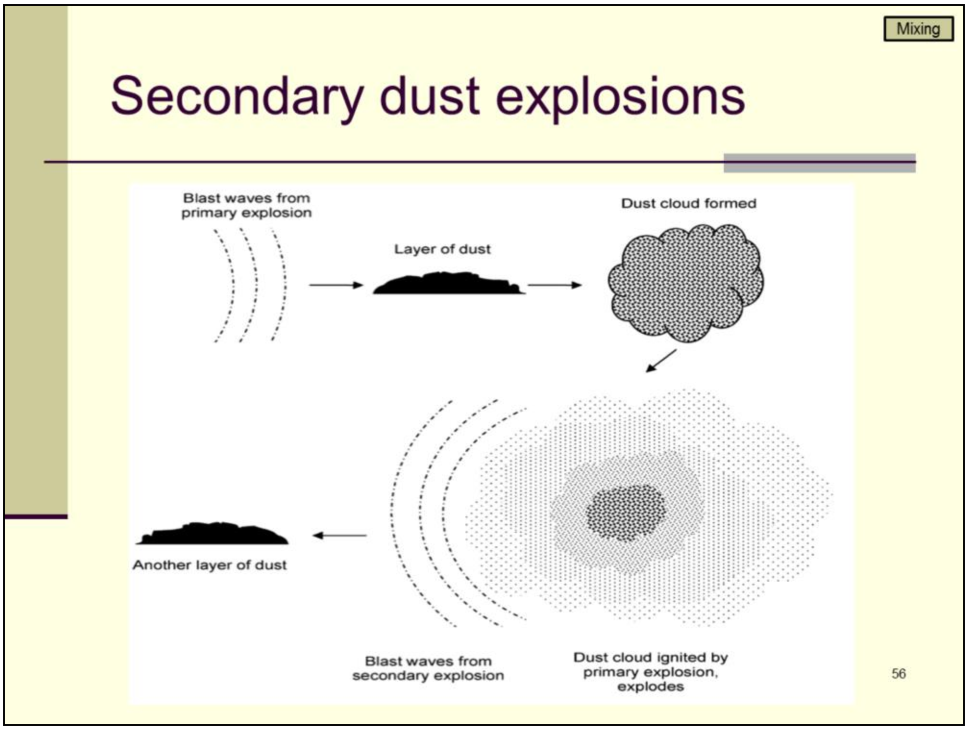
This section covers the various factors affecting dust layer dispersion. The sequence of primary and secondary explosions is explained, and turbulence effects are discussed.



Explosible dust clouds are optically thick. Eckhoff (2003) puts this in practical terms by quoting the observation that a glowing 25-W light bulb cannot be seen through 2 m of a dust cloud at concentrations exceeding 40 g/m^3. Such a concentration is lower than the MEC for many dusts.

Initiation of primary dust explosions therefore usually happens in dust clouds present in process vessels and units such as mills, grinders and dryers – i.e., inside equipment where the conditions of the explosion pentagon are satisfied. The reason for this occurrence is further explained by the figure in the slide. Here, the range of explosible dust concentrations in air at normal temperature and pressure for a natural organic dust (e.g., cornstarch) is compared with the typical range of maximum permissible dust concentrations that are relevant in the context of industrial hygiene, and with a typical density of deposits or layers of natural organic dusts. Clearly, the range of explosible concentrations is orders of magnitude greater than the concentrations permitted in areas inhabited by workers.

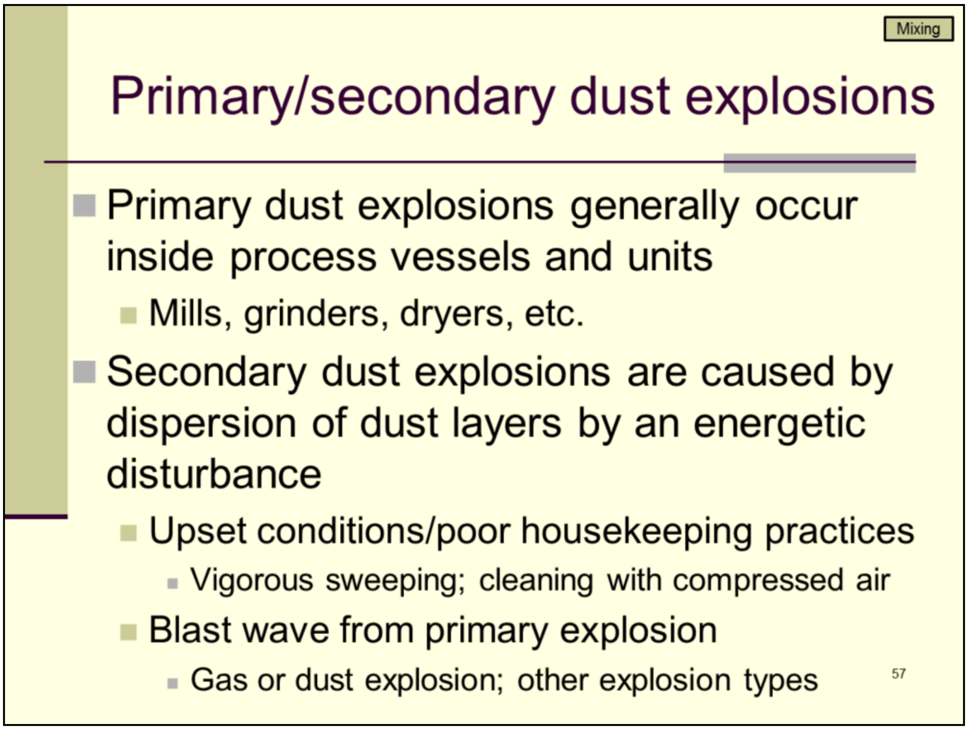
Figure: Eckhoff, R.K., “Dust Explosions in the Process Industries”, 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).



Industry experience tells us that dust explosions also occur in process areas, not just inside process units. A *secondary* explosion can be initiated due to entrainment of dust layers by the blast waves arising from a *primary* explosion as illustrated by the figure in this slide.

The primary event might be a dust explosion originating in a process unit, or could be any disturbance energetic enough to disperse combustible dust layered on the floor and other surfaces (such as improper cleaning practices using compressed air rather than an explosion-proof vacuum).

Figure: Abbasi, T. and Abbasi, S.A., “Dust Explosions – Cases, Causes, Consequences, and Control”, Journal of Hazardous Materials, **140**, 7-44 (2007).



This slide gives a summary of the points made in the previous two slides and accompanying notes. Understanding the concept of primary and secondary dust explosions is one of the most important features of dust explosion risk reduction.

Mixing

Dustiness/dispersibility

Characteristic	Influence on Dispersion
Particle size	Larger diameter → higher settling velocity
Particle specific surface area	Larger specific surface area → lower settling rate
Dust moisture content	Higher moisture content → reduced dispersibility
Dust density	Higher density → higher settling velocity
Particle shape	Asymmetry and roughness → lower settling velocity
Agglomeration processes	Impact effective particle diameter

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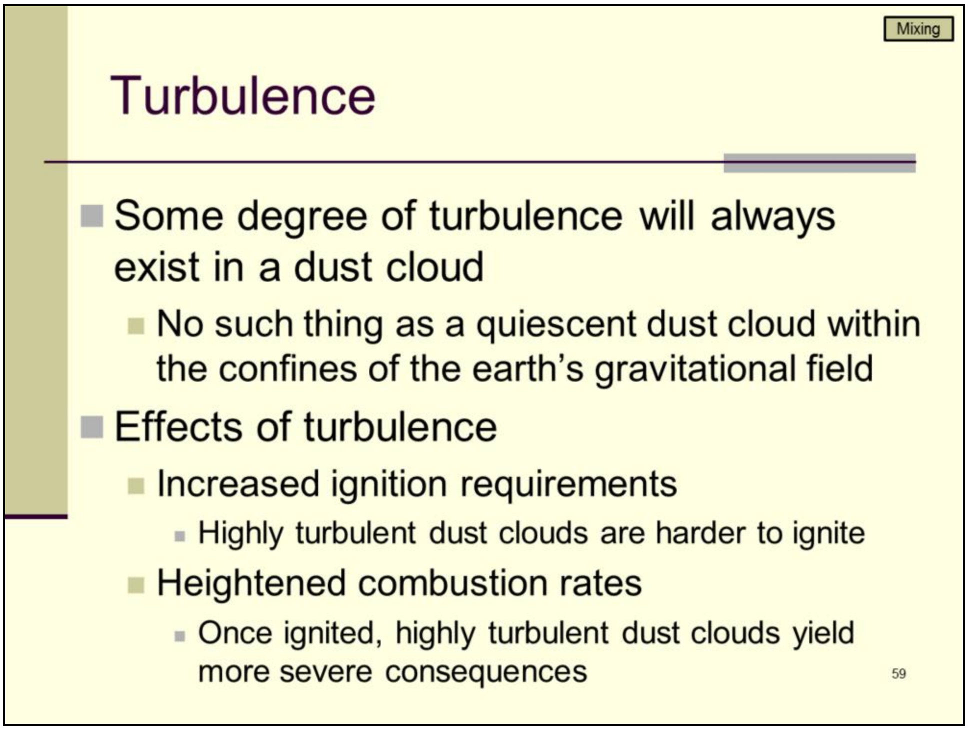
How long a dust cloud remains in suspension depends on its dispersibility or dustiness. Dustiness is defined as the tendency of a dust to form clouds, and is influenced by the six characteristics shown in the table (Klippel, A., Scheid, M. and Krause, U., “Investigations into the Influence of Dustiness on Dust Explosions”, Proceedings of the Ninth International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions, Krakow, Poland (July 22-27, 2012).)

Particle size – For a given dust density, the terminal settling velocity of spherical particles increases with an increase in particle diameter.
Particle specific surface area – Higher specific surface area leads to a lower settling rate because of greater drag force acting on the particles.
Dust moisture content – Cohesion caused by inter-particle adhesion forces results in a decrease in dispersibility with an increase in dust moisture content.
Dust density – For a given particle diameter, the terminal settling velocity of spherical particles increases with dust density.
Particle shape – Features such as asymmetry in particle shape and roughness in surface texture have been shown to result in lower terminal settling velocities than for smooth, spherical particles due to rotational settling and eddy formation. Flocculent or fibrous dusts would be expected to settle at rates dependent on the orientation of the cylindrical-shaped particles to both the flow and gravitational fields.
Agglomeration processes – Two key aspects of the tendency of dusts to agglomerate become important when considering the concept of an effective particle diameter: (i) attraction between particles in dust layers due to inter-particle cohesion forces, and (ii) rapid coagulation of particles in a dust cloud. In the first instance, dispersion of agglomerates into primary particles is made more difficult; the second case means that even if a dust is well-dispersed, the formation of larger agglomerates in suspension remains a possibility.

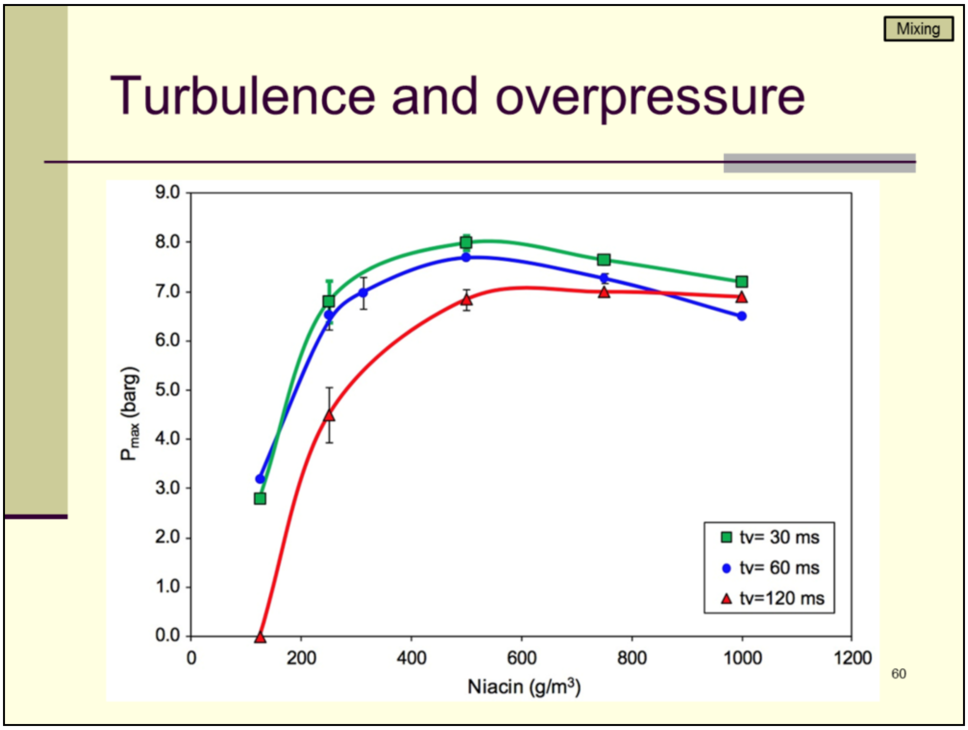
Further references for this slide can be found in: Amyotte, P., “An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace”, Elsevier/Butterworth-Heinemann, Waltham, MA (2013).



Turbulence is the state of rapid, internal random movement of elements within a dust cloud relative to one another. Some degree of turbulence must exist within a dust cloud to allow for fuel and oxidant mixing.

Ignition temperature and ignition energy requirements both increase at higher turbulence levels. There is also more rapid combustion and overpressure development at higher turbulence levels.

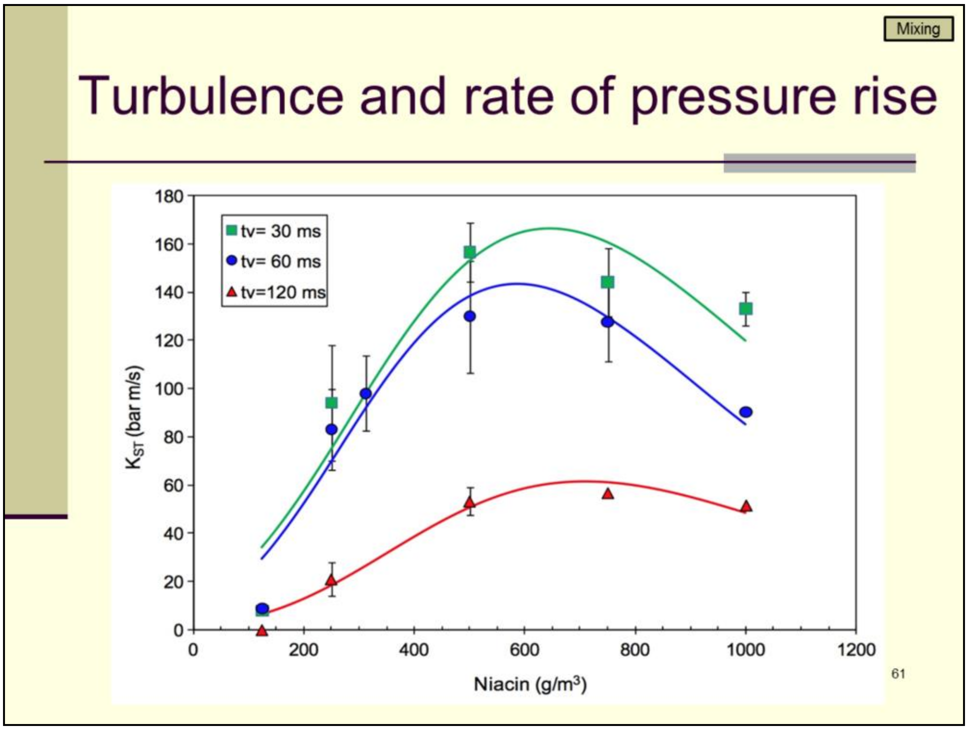
Reference: Eckhoff, R.K., “Dust Explosions in the Process Industries”, 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).



Overpressure is a thermodynamic parameter and as such, turbulence does not have a significant impact on it.

This figure shows the effects of turbulence on explosion overpressure of the pharmaceutical dust, niacin, in the Siwek 20-L apparatus. In the figure, t_v refers to the ignition delay time (time between dust dispersion and ignition source activation). As the delay time increases, turbulence intensity decreases and the dust begins to settle out. We see only a small increase in overpressure with a higher level of turbulence (shorter ignition delay time).

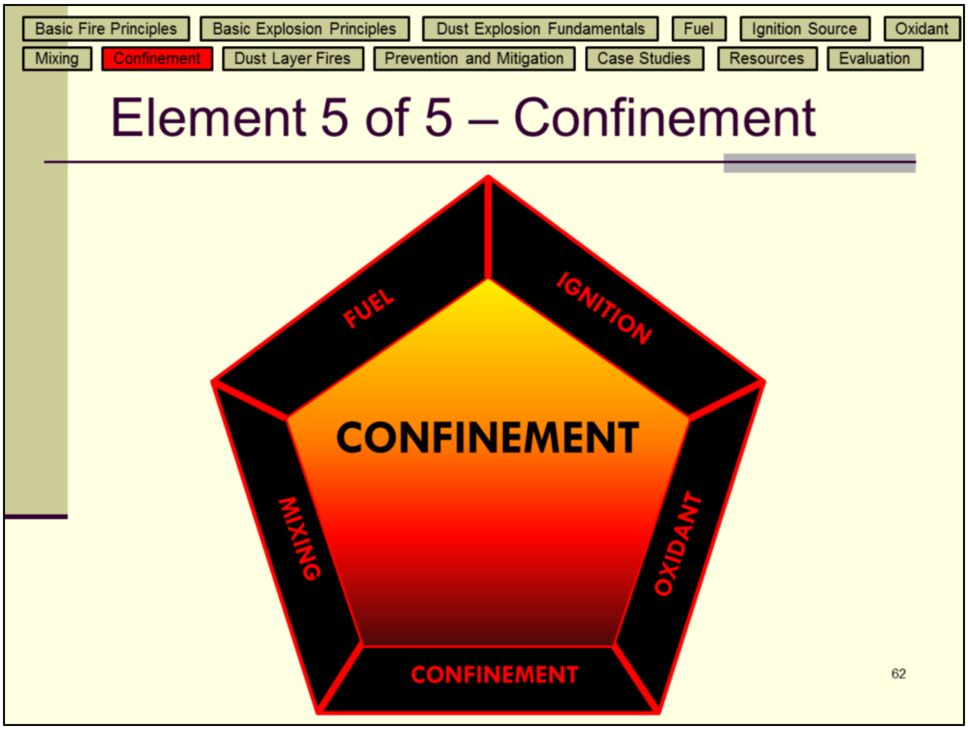
Figure: Sanchirico, R., Di Benedetto, A., Garcia-Agreda, A. and Russo, P., "Study of the Severity of Hybrid Mixture Explosions and Comparison to Pure Dust-Air and Vapour-Air Explosions", Journal of Loss Prevention in the Process Industries, **24**, 648-655 (2011).



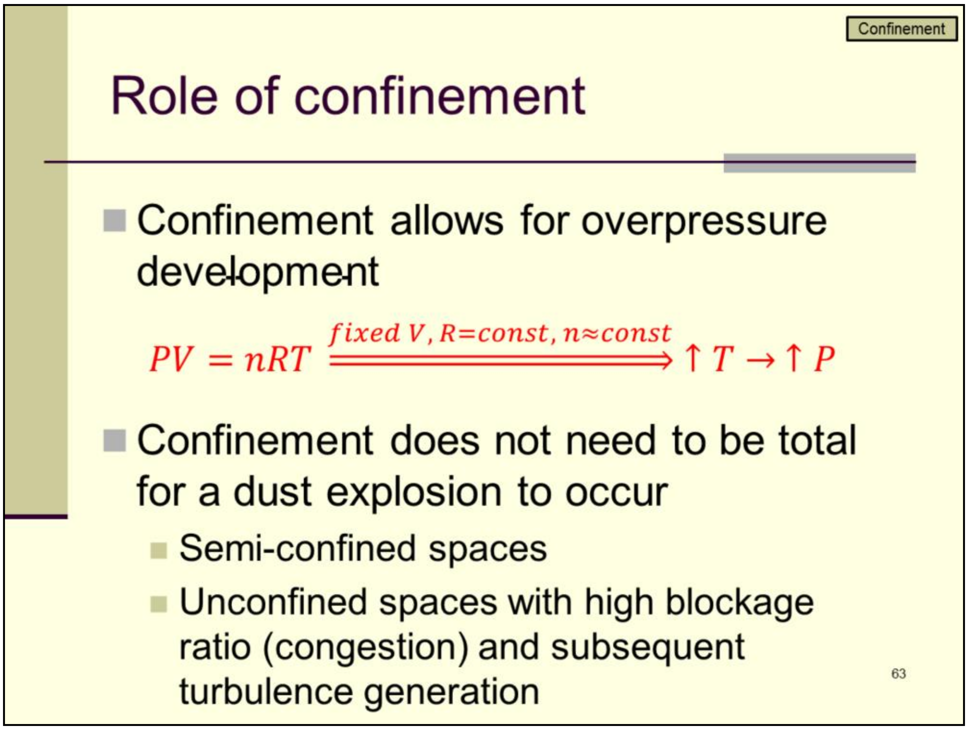
The rate of pressure rise is a kinetic parameter, and is proportional to the flame propagation rate.

This figure shows the effects of turbulence on rate of pressure rise of niacin dust in the Siwek 20-L apparatus. Here, we see that a higher turbulence level (shorter ignition delay time, t_v) leads to a pronounced increase in rate of pressure rise. As the delay time increases, turbulence intensity again decreases and the dust begins to settle out.

Figure: Sanchirico, R., Di Benedetto, A., Garcia-Agreda, A. and Russo, P., “Study of the Severity of Hybrid Mixture Explosions and Comparison to Pure Dust-Air and Vapour-Air Explosions”, Journal of Loss Prevention in the Process Industries, **24**, 648-655 (2011).



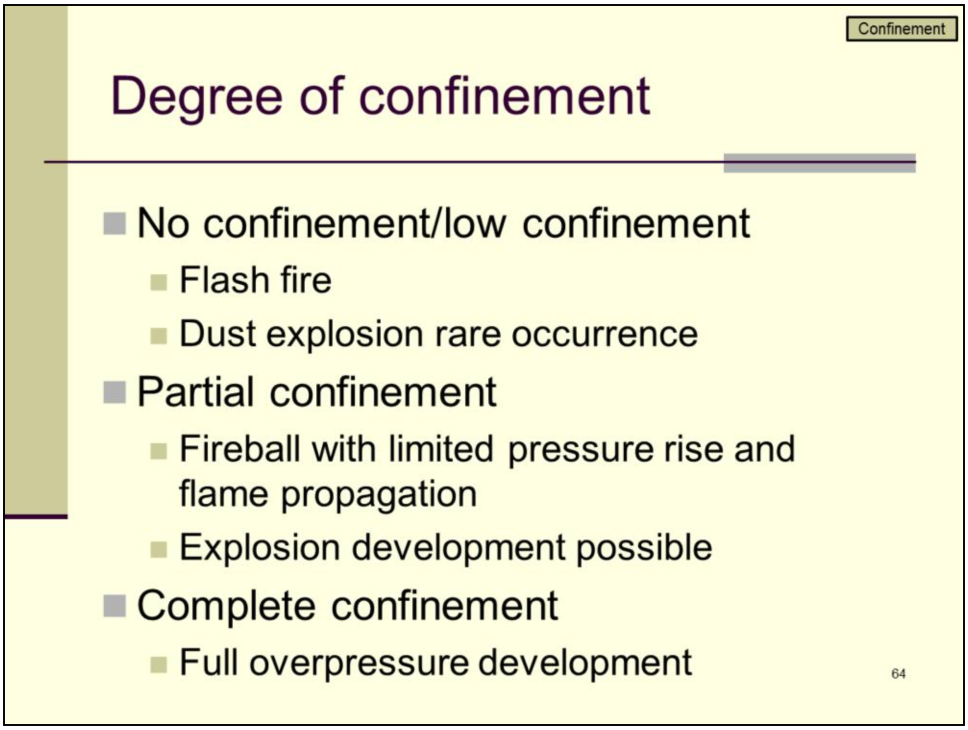
This section examines the role of confinement in the explosion pentagon. Various degrees of confinement and the role of obstacle-generated turbulence (congestion) are described. Venting, the most commonly applied explosion mitigation measure, is also introduced.



Confinement allows for the development of explosion overpressure. The ideal gas law illustrates the role of confinement in overpressure development. The molar amounts of reactants and products do not usually differ significantly and the universal gas constant does not change. So in a confined, fixed-volume system, the pressure and temperature changes would be proportional. In other words, for the equal sign to hold true, the increase in temperature due to combustion must be matched by a proportional change in pressure.

However, confinement does not need to be total (or complete) for a dust explosion to occur. Dust explosions can occur in semi-confined spaces, or in unconfined spaces with a high blockage ratio due to flow obstruction (congestion) and ensuing turbulence generation in the unburned dust cloud (explained further in a later slide).

Further references and points of discussion for this slide can be found in: Amyotte, P., “An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace”, Elsevier/Butterworth-Heinemann, Waltham, MA (2013).



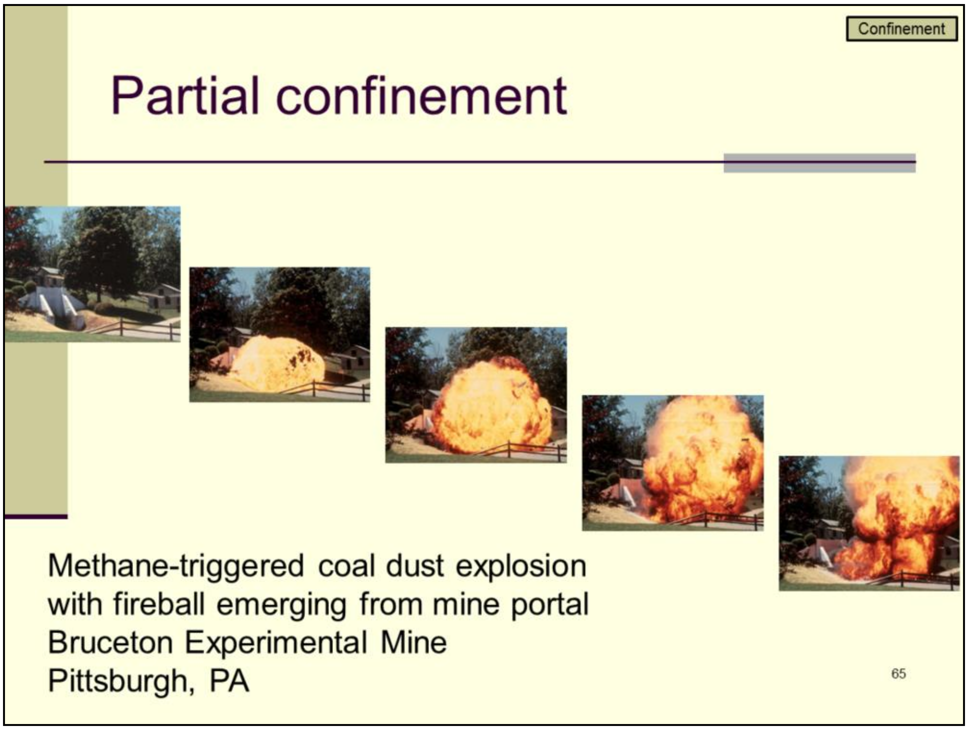
The degree of confinement influences the effects of ignition of a combustible dust.

If there is limited confinement, a flash fire can occur with the potential for secondary fires. An unconfined dust explosion would be expected to be a rare occurrence as pressure development in the dust cloud would need to exceed the rate of pressure dissipation at the cloud edge. A combination of rapid combustion reactions such as from flow obstruction, as well as high dust reactivity would be needed.

If there is partial confinement, a fireball with limited pressure rise inside the enclosure, and flame propagation outside the enclosure may occur. Dust explosions can also occur, such as in underground mine workings.

With complete confinement such as inside process vessels, full overpressure can develop.

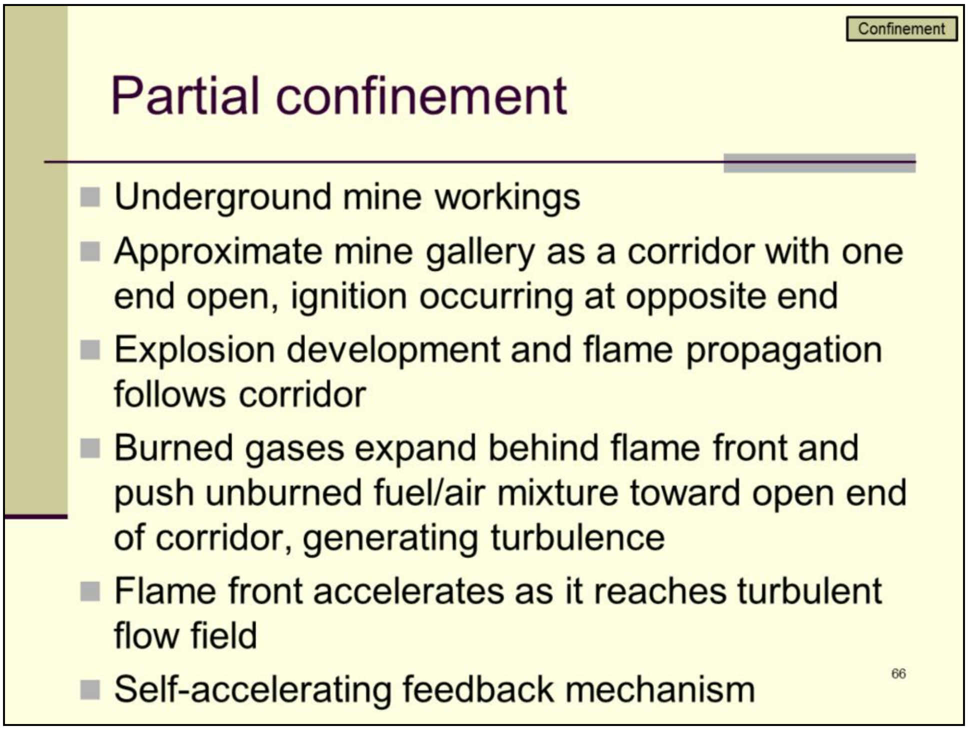
Further references and points of discussion for this slide can be found in: Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/Butterworth-Heinemann, Waltham, MA (2013).



As noted in the previous slide, a dust explosion can occur when there is only partial confinement. An example of such an event would be an explosion in an underground mine. This series of photographs shows the progression of a fireball caused by a methane-triggered coal dust explosion as it emerges from a mine portal.

The next slide explains the underlying physical and chemical phenomena involved in this process.

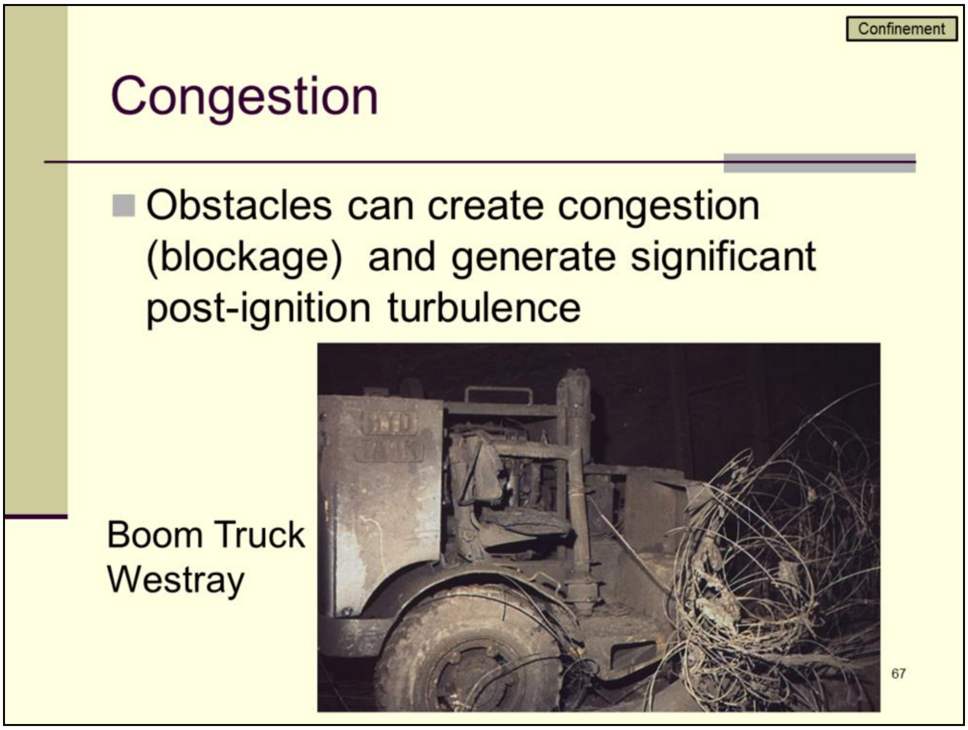
Photographs courtesy of K.L. Cashdollar.



Explosion development and flame propagation in underground mine workings can be approximated by considering a mine gallery to be a corridor with one end open and ignition occurring at the other closed end.

The piston-like effect of the burned gases expanding behind the flame front pushes the unburned fuel/air mixture toward the open end and results in the generation of post-ignition turbulence in the unburned mixture. The advancing flame front then accelerates as it encounters the turbulent flow field with the end-result being a self-accelerating feedback mechanism between flame speed and turbulence level in the unreacted flow field.

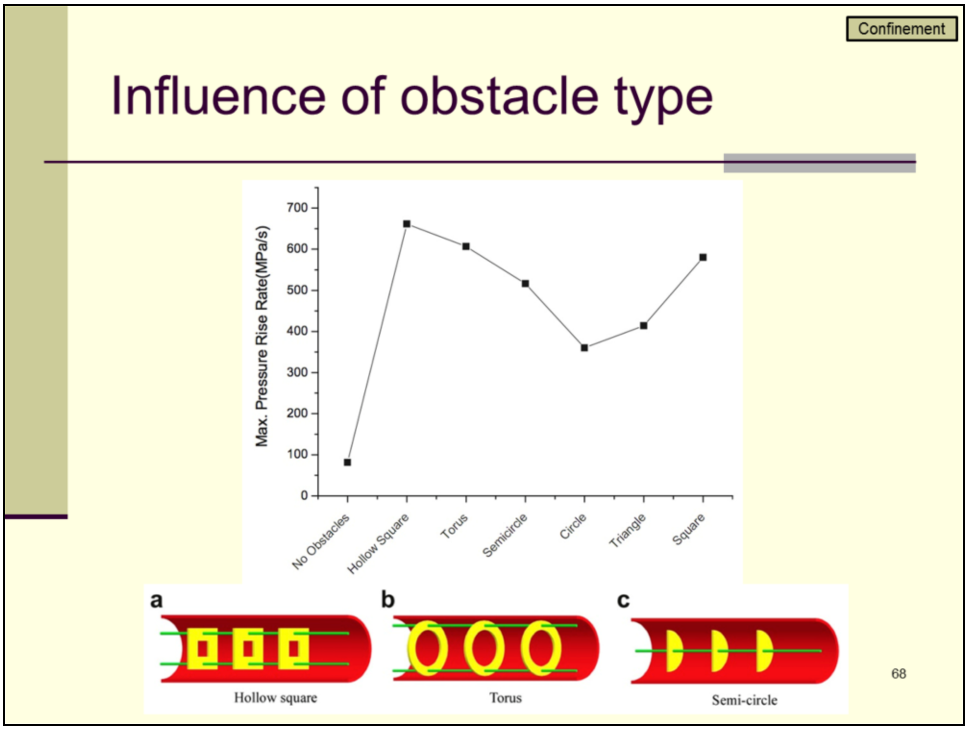
Further references and points of discussion for this slide can be found in: Amyotte, P., “An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace”, Elsevier/Butterworth-Heinemann, Waltham, MA (2013).



Obstacles in the path of an advancing dust flame can create enough congestion or blockage to generate significant post-ignition turbulence. This results in both flame acceleration and increased pressure development.

An example of such a turbulence-generating obstacle is a boom truck (tractor) used in some underground coal mines. The photograph in the slide shows a boom truck post-explosion in the Westray mine (discussed in the Case Studies section of the module).

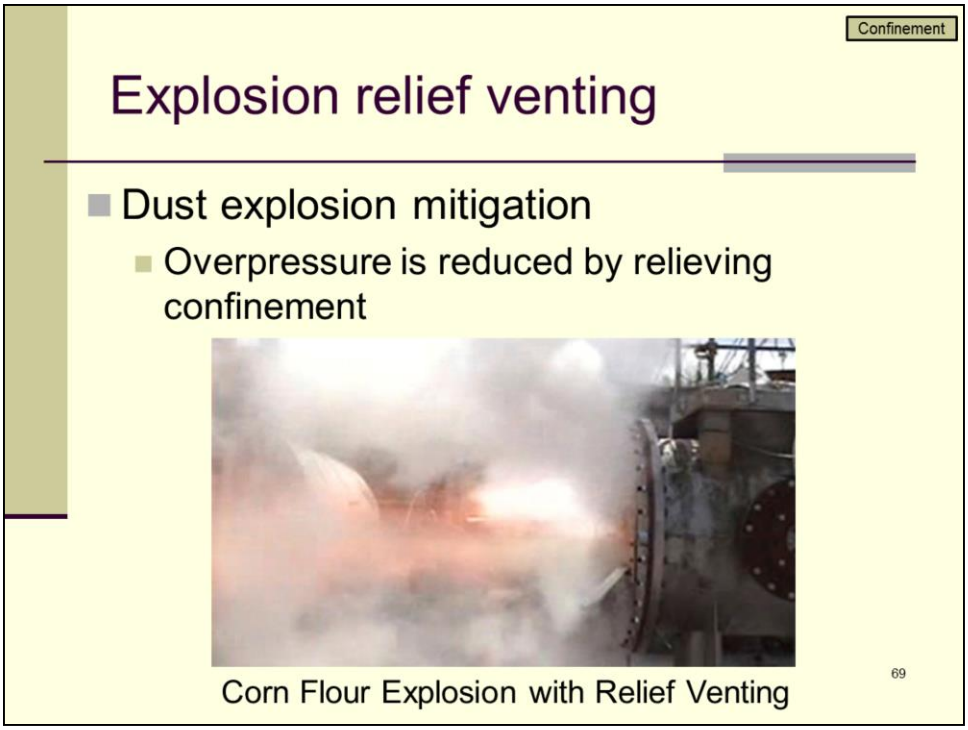
Photograph: Richard, K.P., Justice, “The Westray Story – a Predictable Path to Disaster. Report of the Westray Mine Public Inquiry”, Province of Nova Scotia, Halifax, NS (1997).



These figures shows how different obstacles can influence the rate of pressure rise. The laboratory-scale tests were conducted on coal dust/methane/air mixtures.

As described previously, obstacles create turbulence in the flow of the unburned fuel ahead of the flame. Once the flame reaches this turbulent flow field, the flame surface area is increased, resulting in an enhanced burning rate and higher burning velocity. This in turn creates more turbulence, leading to rapid flame acceleration and heightened rates of pressure rise.

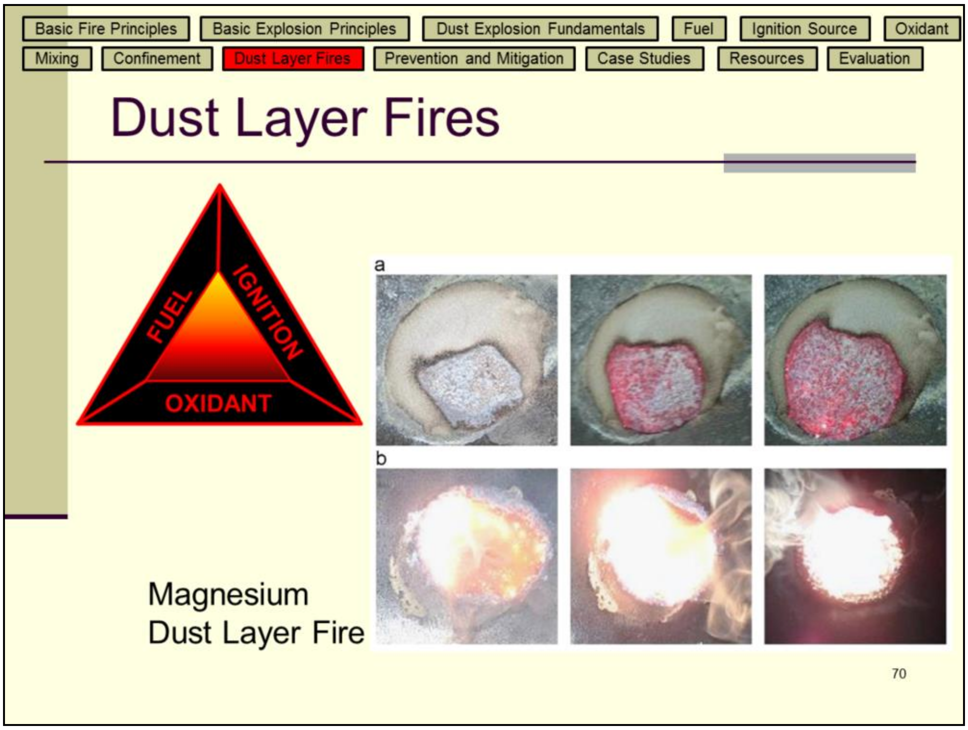
Figures: Zhou, Y., Bi, M. and Qi, F., “Experimental Research into Effects of Obstacle on Methane-Coal Dust Hybrid Explosion”, Journal of Loss Prevention in the Process Industries, **25**, 127-130 (2012).



Explosion relief venting is a common – arguably the most common – approach to dust explosion mitigation (protection). Venting allows for reduction in overpressure as a result of confinement relief. This topic will be explored further in the module section on Prevention and Mitigation.

The photograph in the slide shows a vented corn flour dust explosion. It also illustrates the basic idea behind venting. Although flame, combustion products and unburned dust are ejected through the vent, the integrity of the vented enclosure is maintained.

Photograph: Holbrow, P., “Dust Explosion Venting of Small Vessels and Flameless Venting”, Process Safety and Environmental Protection, **91**, 183-190 (2012).

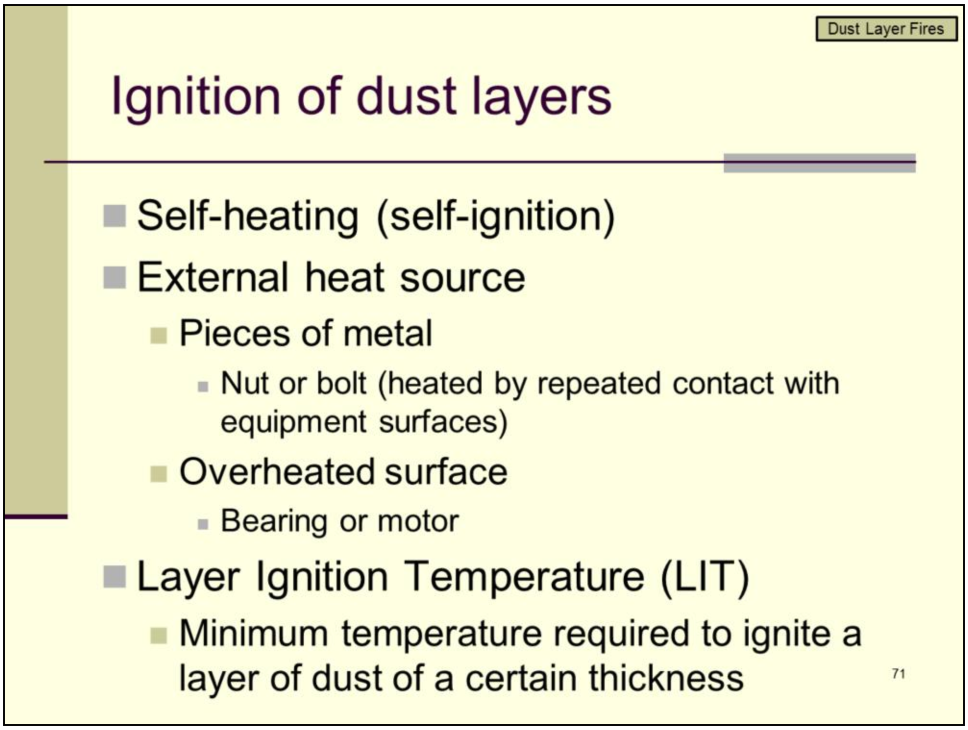


In this section, we briefly examine the issue of dust layer fires. Self-ignition of dust layers and ignition by an external source are discussed. The layer ignition temperature or LIT is defined and the effect of layer thickness on LIT is illustrated. Finally, the concept of normalization of deviance is used to explain why dust layer fires are sometimes ignored as predictors of larger fires or explosions.

The fire triangle is again pertinent to the discussion here as explained on the next slide. Note that there are no mixing and confinement elements involved. As we have just seen in the previous section, it is possible for a dust/air cloud to burn rather than explode when confinement is low. This event is termed a flash fire and is a different scenario than layer fires as presented in this section.

The figure in the slide shows a magnesium dust layer fire. The first stage (a) involves slow, lower temperature combustion. The second stage (b) involves rapid, higher temperature combustion of magnesium gas generated from the layer.

Figure: Gang, L., Chunmiao, Y., Peihong, Z. and Baozhi, C., “Experiment-Based Fire and Explosion risk Analysis for Powdered Magnesium Production Methods’’ Journal of Loss Prevention in the Process Industries, **21**, 461-465 (2008).



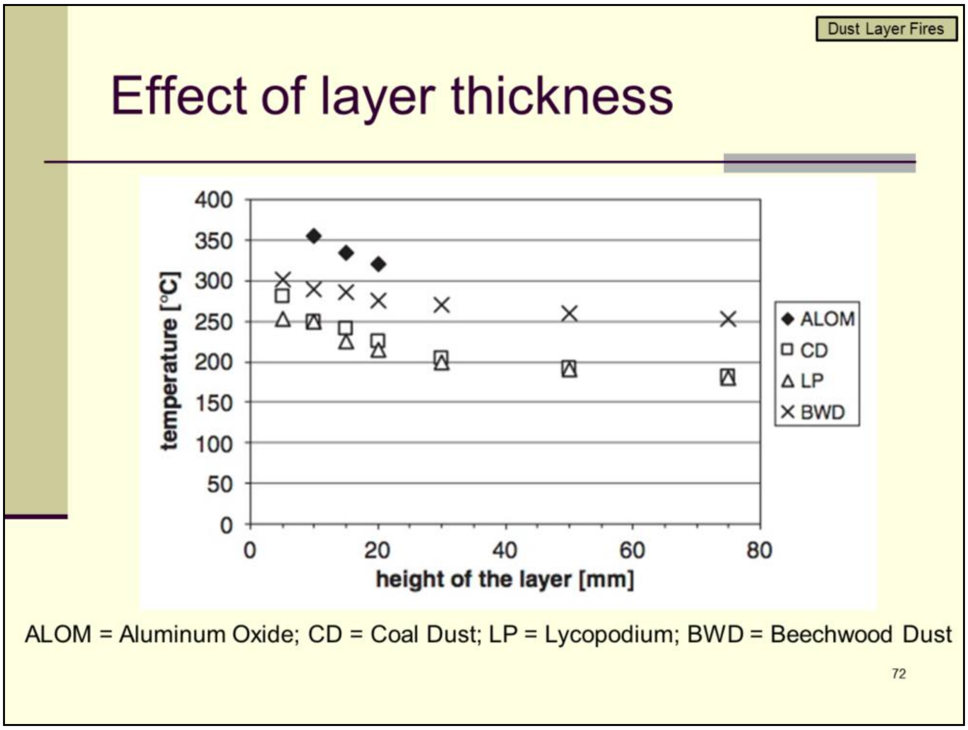
Dust layer fires involve a combustible dust, an oxidant (typically oxygen in air), and an Ignition mechanism.

There are two ignition mechanisms for dust layers: self-heating (or self-ignition, or spontaneous combustion) and an external heat source. Self-ignition is described in a later slide.

Eckhoff (2003) gives two possible industrial scenarios for a hot object (external heat source) being in close proximity to a combustible dust: (i) a piece of metal (e.g., a nut or bolt) present in a bulk powder stream and which has been heated by repeated contact with the process equipment boundaries, and (ii) an overheated surface (e.g., a bearing or motor) covered with a layer of dust.

In the case of a dust layer that has accumulated on a heated surface, we can define the LIT (layer ignition temperature) as the lowest hot-surface temperature that will cause ignition of a dust layer having a specified thickness. There is an ASTM test method to measure LIT.

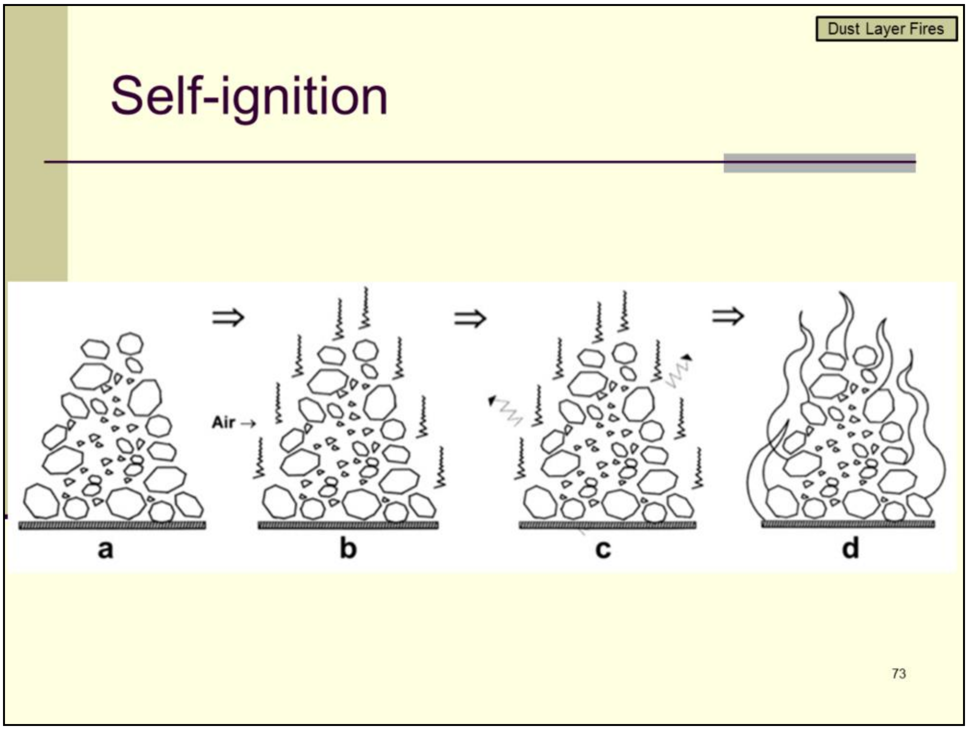
Reference: Eckhoff, R.K., "Dust Explosions in the Process Industries", 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).



The LIT of a given dust, like other explosion parameters (e.g., MIE), is not an intrinsic property of the material. Nevertheless, LIT values provide helpful information for industrial practice.

It must be remembered that LIT is a function of layer thickness. The figure in this slide shows LIT data for various dusts over a range of layer thicknesses (or heights). Clearly, LIT values are higher for thinner layers.

Figure: Querol, E., Torrent, J.G., Bennet, D., Gummer, J. and Fritze, J.-P., "Ignition Tests for Electrical and Mechanical Equipment Subjected to Hot Surfaces", Journal of Loss Prevention in the Process Industries, **19**, 639-644 (2006).

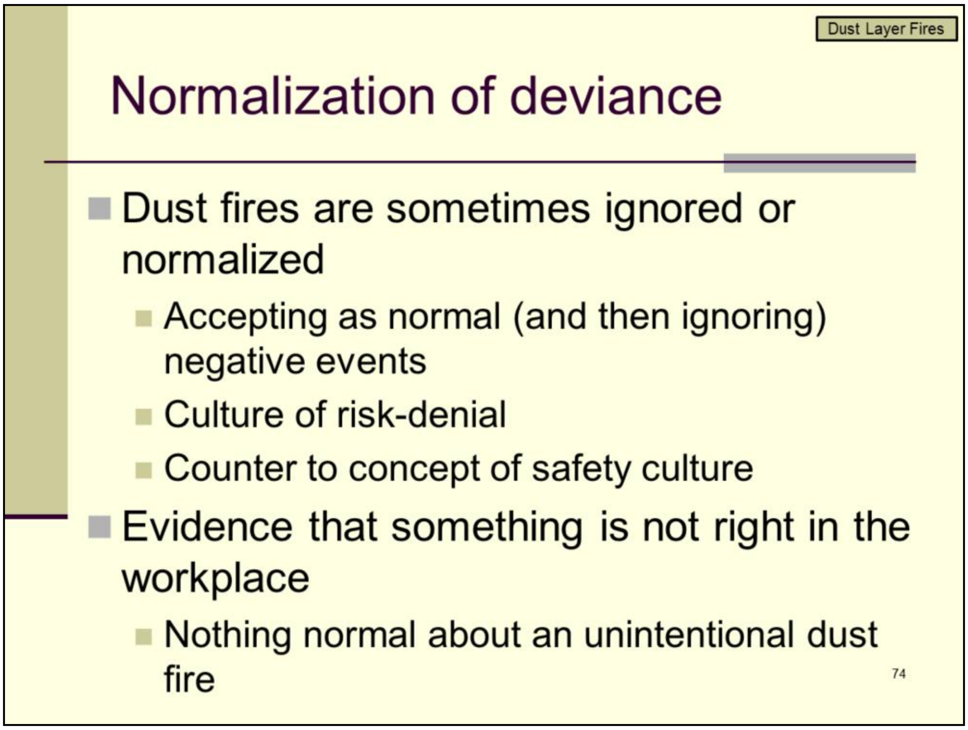


An external heat source may not be needed for layer ignition to occur. Under certain conditions, a dust pile can self-heat and then ignite. To initiate self-heating, there must be sufficient porosity for air to enter the pile and react with the fuel. Heat must be generated faster than it is lost. Once a critical temperature is achieved, ignition can occur due to thermal runaway.

In the figure shown in the slide we see:

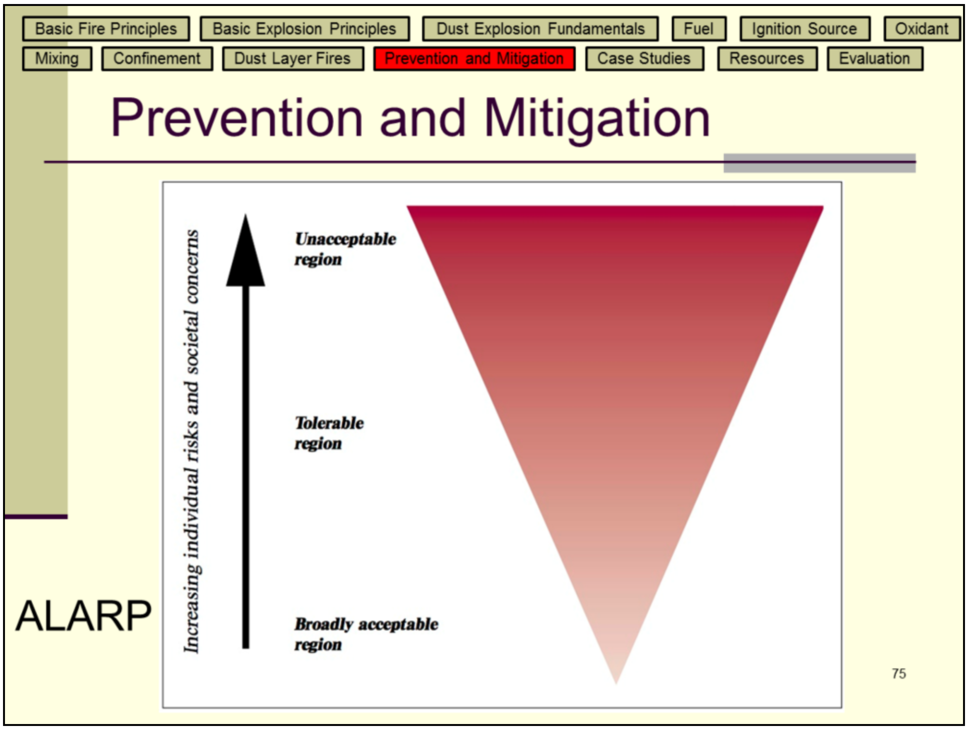
(a) a coal pile having various particle sizes,
(b) air ingress and initial self-heating,
(c) heat losses by conduction, convection and radiation at rates not exceeding the rate of heat generation, and
(d) self-ignition at some critical temperature.

Figure: Sipila, J., Auerkari, P., Heikkila, A.-M., Tuominen, R., Vela, I., Itkonen, J., Rinne, M. and Aaltonen, K., “Risk and Mitigation of Self-heating and Spontaneous Combustion in Underground Coal Storage”, Journal of Loss Prevention in the Process Industries, **25**, 617-622 (2012).



Dust layer fires generally do not cause the same degree of damage and injury as dust explosions. As such, they might be ignored, or become accepted as normal to operations – simply “the cost of doing business”, or “the way things are done around here”.

This phenomenon is termed *normalization of deviance* and is part of a workplace culture known as *risk-denial*. Normalizing evidence that in fact should be seen as a predictor or warning sign of an impending catastrophe, is completely counter to a well-functioning safety culture. We return briefly to this topic in the next section on Prevention and Mitigation.



This section presents techniques and strategies for preventing and mitigating dust explosions. **Although the discussion is specific to dust explosions, the basic principles illustrated are also applicable to gas and vapour explosions.**

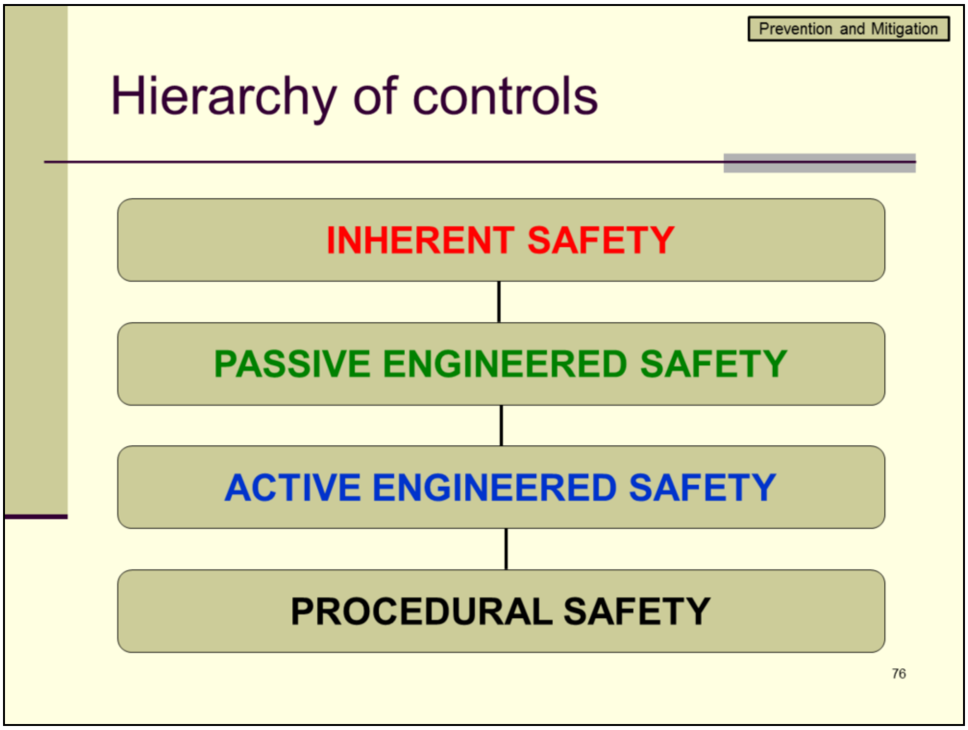
We begin with a look at an overall approach to risk reduction known as the hierarchy of controls. The various levels in the hierarchy are then examined: (i) inherent safety, (ii) passive engineered safety, (iii) active engineered safety, and (iv) procedural safety. We conclude with the concepts of a safety management system and safety culture.

Prevention and mitigation efforts are aimed at risk reduction. Prevention deals with lessening the likelihood of occurrence of a dust explosion and mitigation with protecting people and plant from the consequences of such an event. In spite of our best efforts to eliminate hazards, there will always be residual risk that must be properly managed.

The figure in this slide gives a representation of the ALARP (As Low As Reasonably Practicable) principle. Vinem (2012) explains that use of the ALARP principle requires examination of both risk levels and risk prevention/mitigation costs, with risk reduction measures being implemented according to cost effectiveness considerations. Thus, a process can be made safer than it was before the introduction of additional safety measures but it cannot be made 100 % safe. More to the point, the potential benefits of attempting to drive process risk to zero will likely be grossly disproportionate to the cost involved. We should talk about safer alternatives, not safe processes.

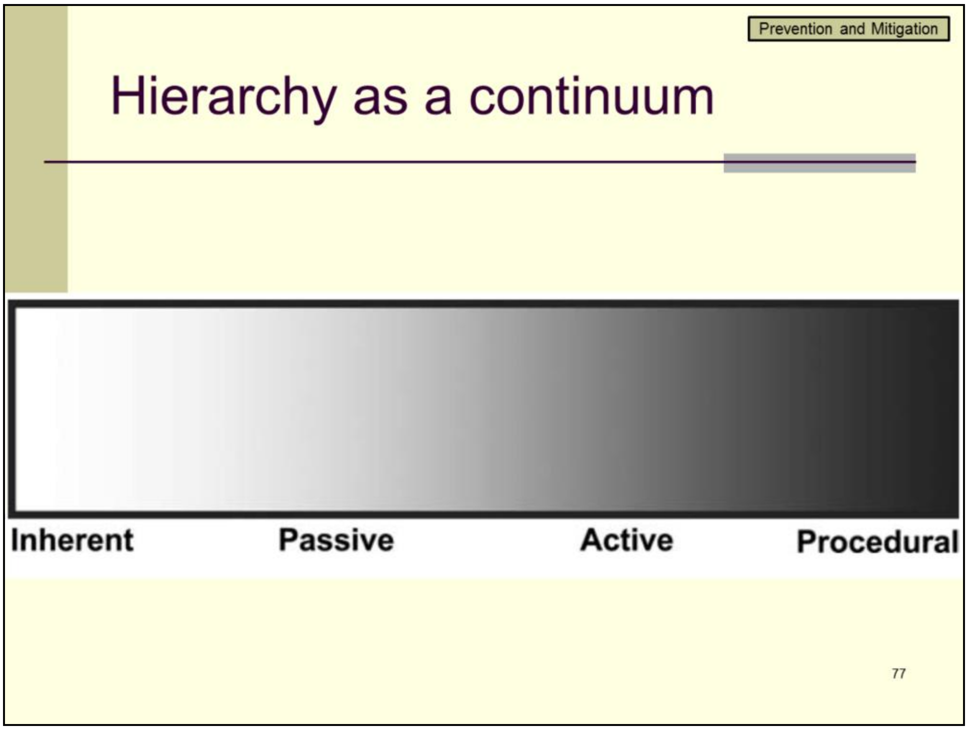
Figure: Vinem, E., "Ethics and Fundamental Principles of Risk Acceptance Criteria", Safety Science, **50**, 958-967 (2012).

Much of the material in this section is drawn from: Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/Butterworth-Heinemann, Waltham, MA (2013). Original references can be found there.



The hierarchy of controls is an ordered arrangement of general risk reduction measures. Inherent safety, being the most effective approach to risk reduction, sits at the top of the hierarchy; it is followed in order of decreasing effectiveness by passive engineered safety devices (e.g., explosion relief vents), then active engineered safety devices (e.g., automatic suppression systems), and finally procedural safety measures (e.g., ignition source control by hot-work permitting).

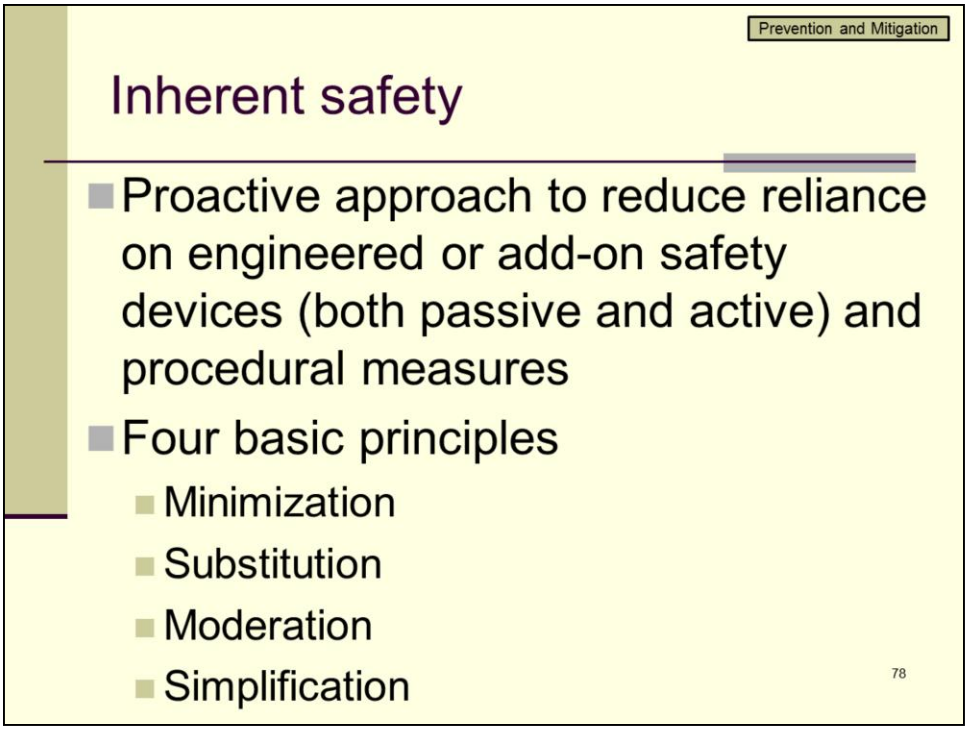
Each of the four levels, with specific examples for dust explosion control, is explained in this section.



The figure in this slide illustrates an often overlooked feature of the hierarchy of controls – that it actually represents a continuum of safety measures. It is helpful to view the hierarchy as a spectrum of options rather than as distinct entities having sharply defined boundaries. Hendershot (2010) remarks that while people may disagree about the category in which a given approach falls, what really matters is whether the approach is effective from an engineering design viewpoint.

For example, use of safe work procedures is a procedural safety measure. If the procedures are clearly written and easy to follow, this can also be viewed as an application of the inherent safety principle known as *simplification*. Also, some might view housekeeping (in which dust accumulations are removed from the workplace) as purely a procedural safety measure, whereas others would see overtones of the inherent safety principle of *minimization*.

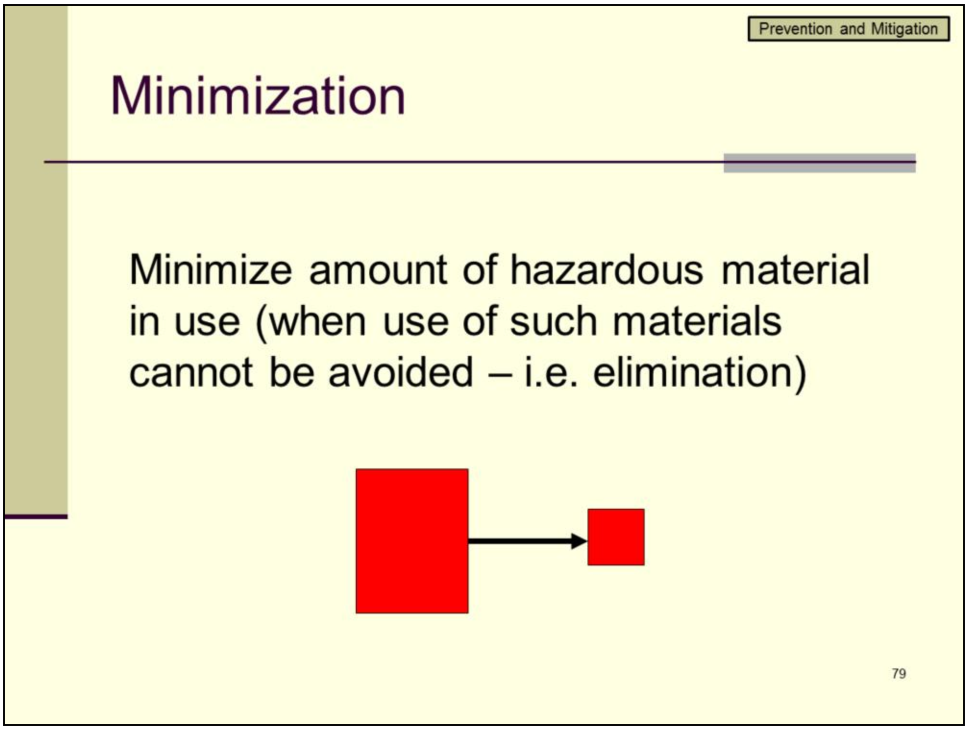
Figure: Hendershot, D.C., "A Summary of Inherently Safer Technology", Process Safety Progress, **29**, 389-392 (2010).



Inherent safety is a proactive approach in which hazards are eliminated or lessened so as to reduce risk with decreased reliance on engineered (add-on) devices and procedural measures.

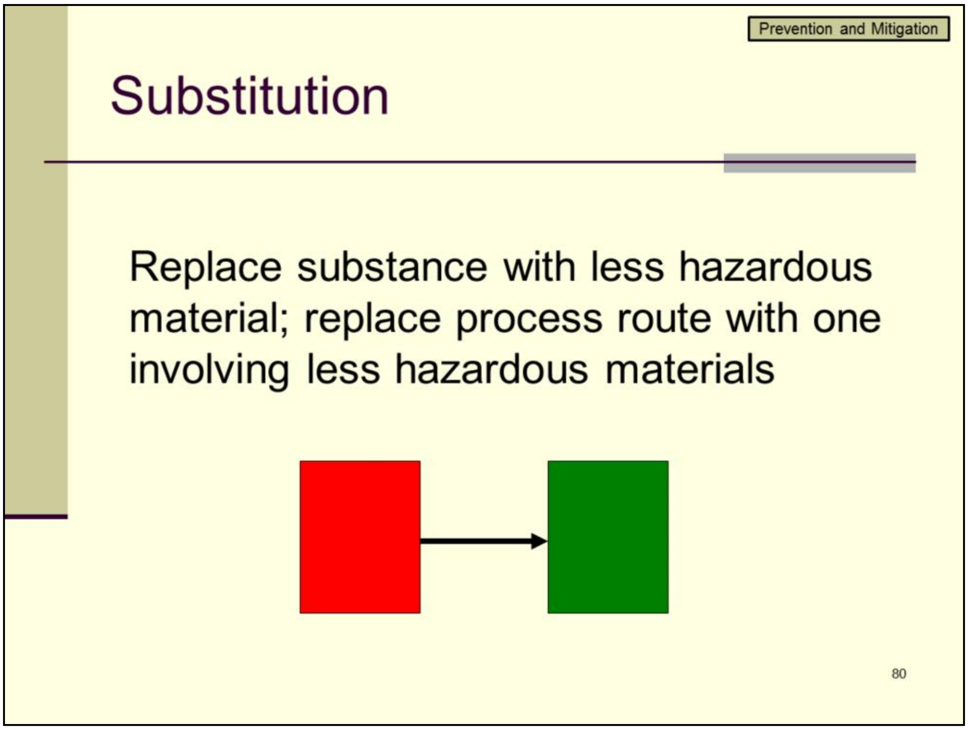
There are a number of inherent safety principles, of which the most fundamental ones are:

- Minimization,
- Substitution,
- Moderation, and
- Simplification.



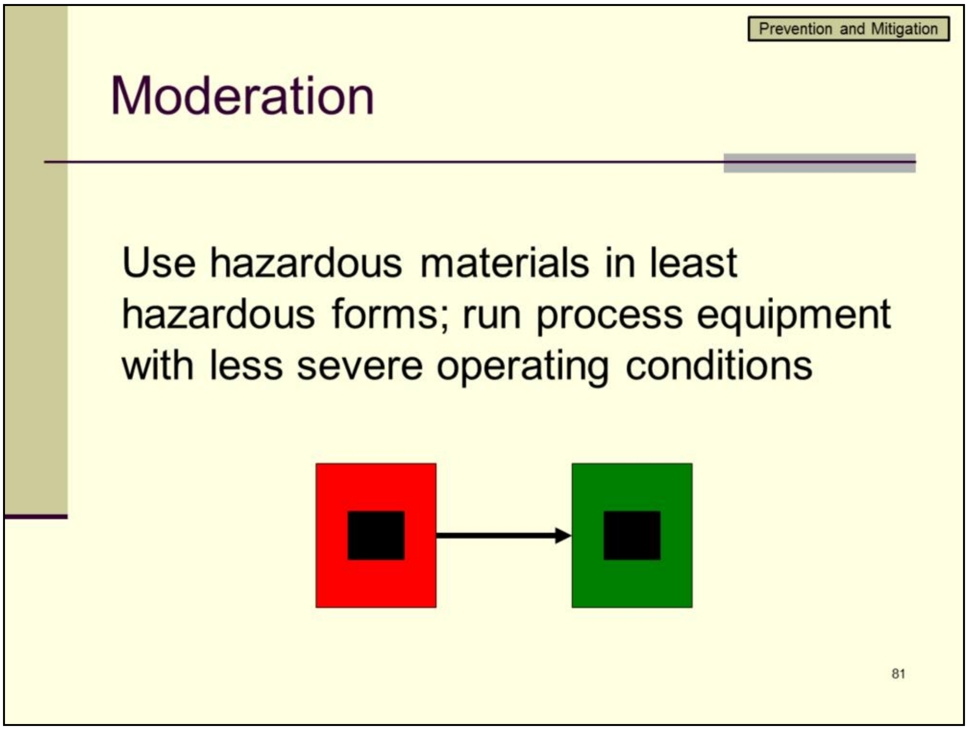
With respect to dust explosions, minimization includes:

- Avoidance of the formation of combustible dust clouds. Because of the large quantities of particulate material present in powder handling equipment (which as previously described is where most primary dust explosions occur), it can be difficult, however, to achieve operation at dust concentrations below the MEC.
- Removal of dust deposits (avoidance of dust layers). Minimization of fuel loadings in this case is critical to the prevention of secondary dust explosions.



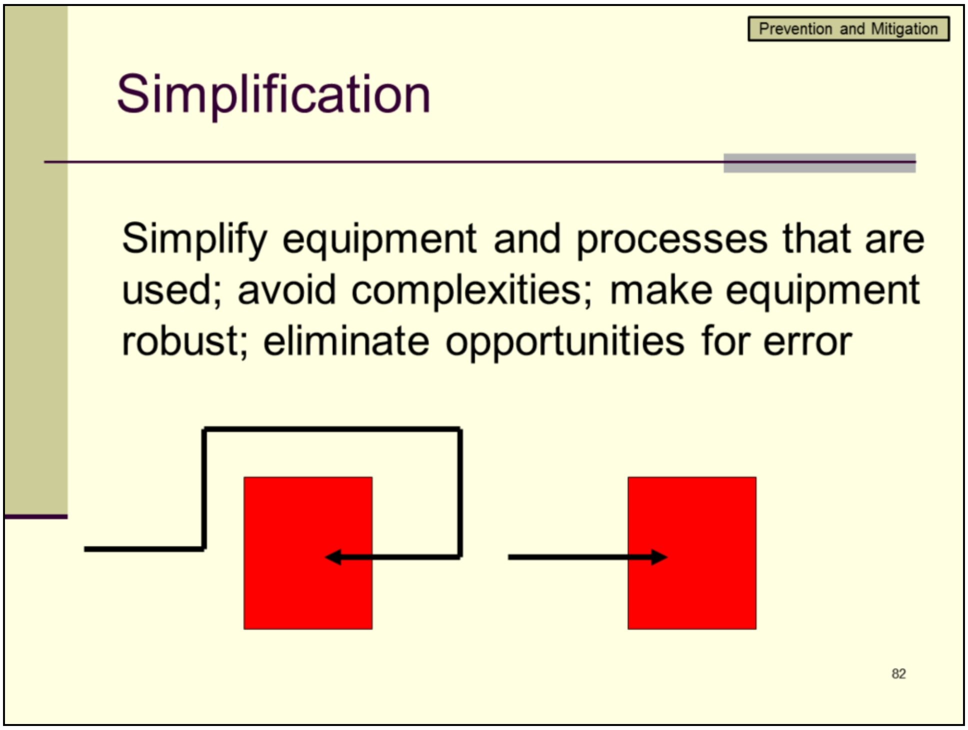
With respect to dust explosions, substitution includes:

- Replacement of bucket elevators and other mechanical conveying systems with dense-phase pneumatic transport.
- Substitution of process hardware with less hazardous materials of construction (e.g., avoiding unnecessary use of insulating materials).
- Use of mass flow silos and hoppers rather than funnel flow silos so as to avoid undesired particle segregation and uncontrolled dust cloud formation.
- Alteration of a process route that involves handling an explosible powder (e.g., earlier introduction of an inert powder that is a component of the final product).
- Replacement of a combustible dust with one that is less hazardous. While this may be difficult to achieve in many cases, opportunities can arise when other factors such as cost motivate process change. For example, petroleum coke is a safer fuel than higher volatile-matter coal (from the perspective of rate of pressure rise). When used in a blended fuel as a partial replacement for pulverized coal in the feed to utility boilers, this inherent safety benefit of petroleum coke is evident.



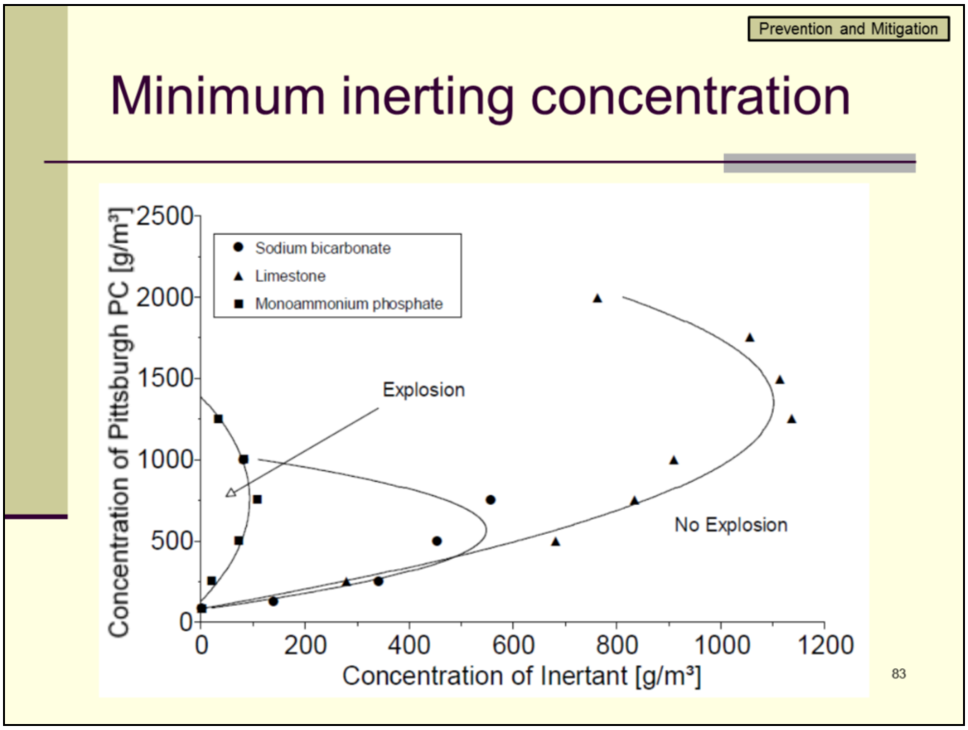
With respect to dust explosions, moderation includes:

- Altering the composition of a dust by admixture of solid inertants (pre-explosion); an example is shown in a later slide (Minimum Inerting Concentration).
- Increasing the dust particle size so as to decrease its reactivity.
- Avoiding the formation of hybrid mixtures of combustible dusts and flammable gases.
- Using powders in paste or slurry form.



With respect to dust explosions, simplification includes:

- Employing the concept of error tolerance by designing process equipment robust enough to withstand process upsets and other undesired events (e.g., shock- or pressure-resistant design). An example here is the hammermill shown in the Dust Explosion Fundamentals section.
- Ensuring information on the hazardous properties of combustible dusts is clear and unambiguous (e.g., by means of thorough and complete Safety Data Sheets).



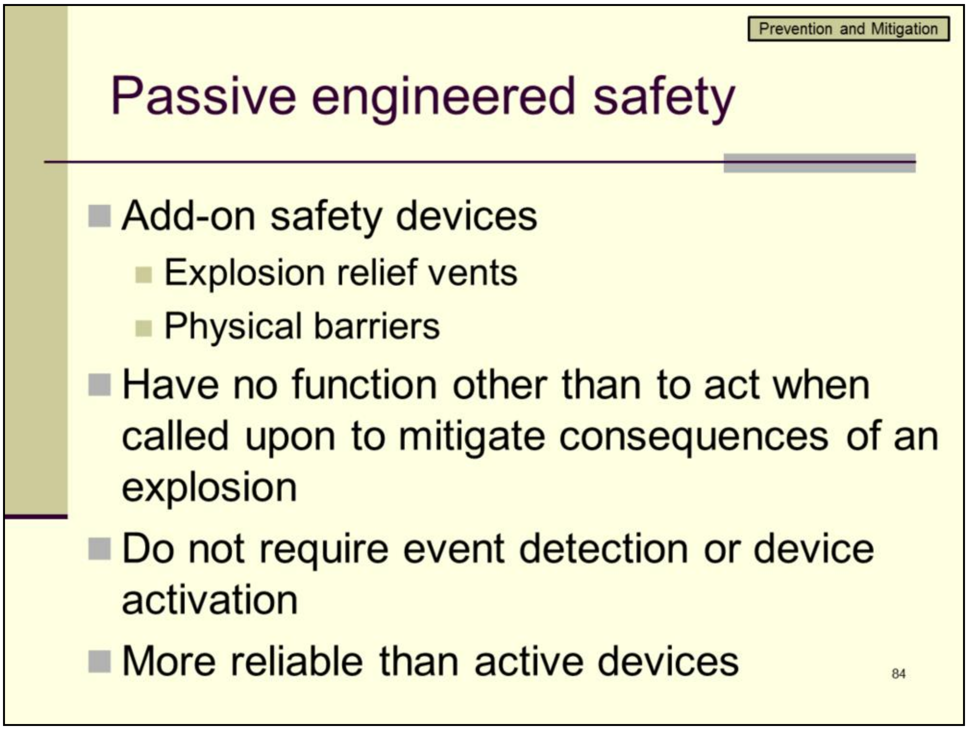
As we just saw, the direct mixing of a combustible dust and a non-combustible dust (inertant) is an application of the inherent safety principle of moderation. The mixing is done pre-explosion to in fact prevent an explosion from occurring. Inerting in this manner is conducted in coal mines to render coal dust non-explosible by mixing it with sufficient quantities of inert rock or stone dust (such as limestone or dolomite). Of course, this technique cannot be used if the dust is the desired product and must be free of contaminants (for example, in the food processing industry).

The amount of inertant needed depends on the actual inerting mechanism – thermal (heat sink) or chemical (reaction termination). The figure in this slide shows the results of testing conducted to determine the minimum inerting concentration (MIC) for mixtures of Pittsburgh pulverized coal dust and each of three inertants – limestone, sodium bicarbonate (SBC) and monoammonium phosphate (MAP).

The area to the left of each curve represents the explosible region for the fuel/inertant mixture. The area to the right of each curve represents the non-explosible region; here there is sufficient inertant to prevent an explosion. The nose of each curve (or envelope) represents the least amount of inertant that would prevent an explosion regardless of fuel concentration – i.e., the MIC.

The figure clearly illustrates that for inerting of Pittsburgh pulverized coal, limestone is the least effective inertant and MAP is the most effective. Limestone is a pure thermal inhibitor whereas MAP exhibits both thermal and chemical inhibition.

Figure: Dastidar, A.G., Amyotte, P.R., Going, J. and Chatrathi, K., “Flammability Limits of Dusts - Minimum Inerting Concentrations”, Process Safety Progress,**18**, 56-63 (1999).



The passive engineered safety level in the hierarchy of controls involves the use of safety devices that are added on to the process/facility unit. These devices do not play a production role; rather their extremely important role is to function in accordance with their design purpose to mitigate explosion consequences and protect people and plant.

Passive devices do not require detection of the explosion or activation of moving parts to perform their intended function. As such, they are more reliable than active engineered devices (described later). Like any mechanical device, however, passive engineered features must be properly designed, installed and maintained.

Examples include explosion relief vents to relieve overpressure (mitigation), and physical barriers to limit the propagation of flame and damaging overpressures downstream (mitigation).

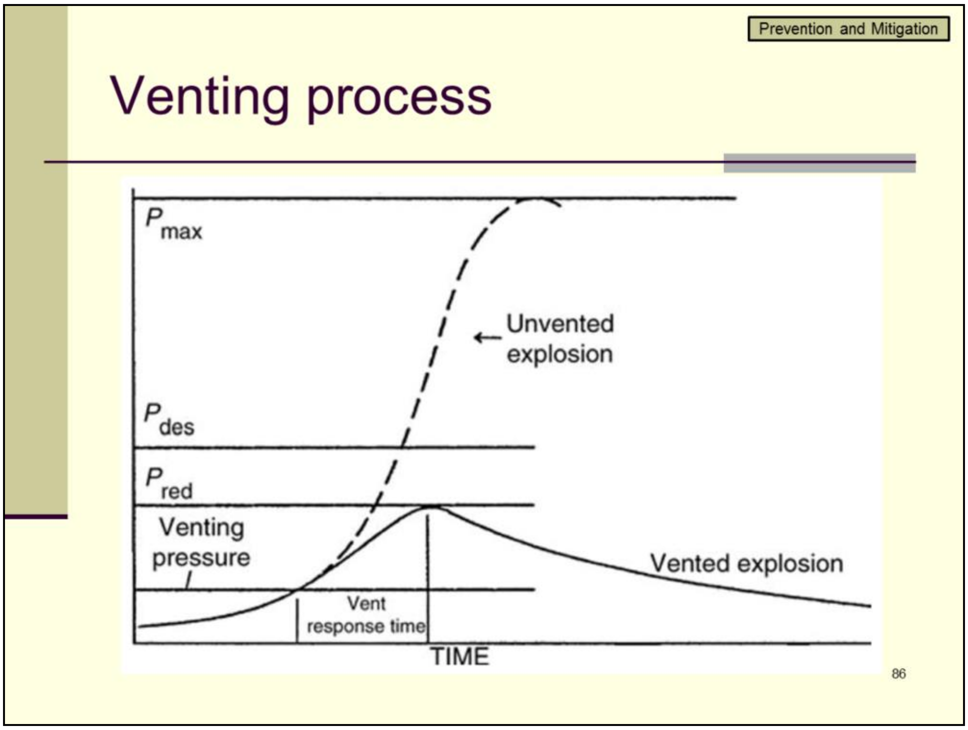
Venting is the most common approach used to mitigate dust explosion overpressure. As we saw in the Containment section, this is achieved by relieving the confinement criterion of the explosion pentagon. We have also previously seen the above photograph in the Containment section as an example of venting in practice.

An explosion vent is a weak area in the wall of a building (e.g., a relief panel) or a dust-handling unit (e.g., a rupture disk). It is important to properly size the vent; acquiring data from standardized explosion testing of the specific dust is required to perform this task.

Undersized vents may be unable to sufficiently mitigate an explosion as the design pressure of the enclosure will be exceeded. The vent must also be designed to open without obstruction, as a possible obstruction will keep the degree of confinement too high to allow for sufficient overpressure relief.

The protection of plant personnel from relieved overpressure and the expelled mixture of combustion products and burning and unburned dust (as shown in the photograph in the slide), must be taken into account. One approach is to use vent ducting to eject any dust, whether burned, burning or unburned, to a safer location. Another approach is flameless venting, which is described in a later slide.

Photograph: Holbrow, P., “Dust Explosion Venting of Small Vessels and Flameless Venting”, Process Safety and Environmental Protection, **91**, 183-190 (2012).



This figure illustrates the venting process in schematic format.

P_{max} = maximum explosion pressure generated in the unvented enclosure

P_{des} = maximum pressure the protected enclosure can withstand

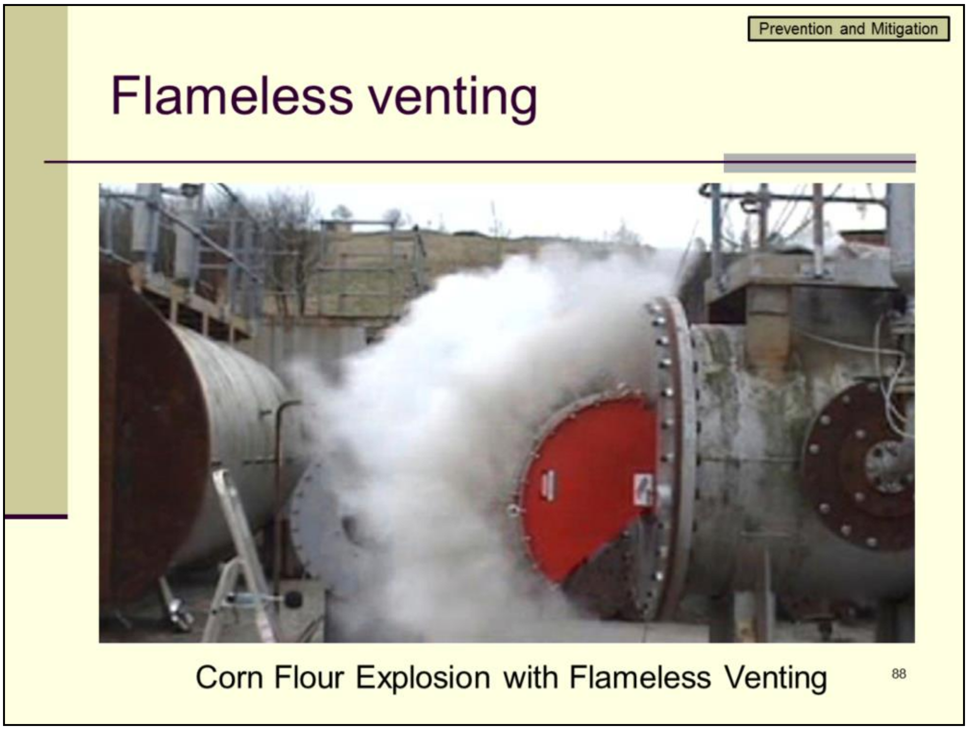
P_{red} = maximum pressure allowed to be generated in the enclosure during explosion

Venting pressure = pressure at which the vent opens (also known as P_{stat})

Figure: Pekalski, A.A., Zevenbergen, J.F., Lemkowitz, S.M. and Pasman, H.J., "A Review of Explosion Prevention and Protection Systems Suitable as Ultimate Layer of Protection in Chemical Process Installations", Process Safety and Environmental Protection, **83**, 1-7 (2005).

These are pictures of typical relief panels and rupture disks (i.e., explosion relief vents).

Images courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).



Flameless venting can help to prevent the ejection of dust and flames through the opening of the relief vent. This is achieved by means of a flame arresting device composed of mesh layers with quenching channels that is fitted in conjunction with the vent.

The photograph in this slide shows the same test rig as seen previously, only this time it is fitted with both a relief vent and a flame arrestor. Here we see the effectiveness of the flameless venting device in eliminating flame propagation through the vent and permitting the passage of only smoke, water vapour and some dust.

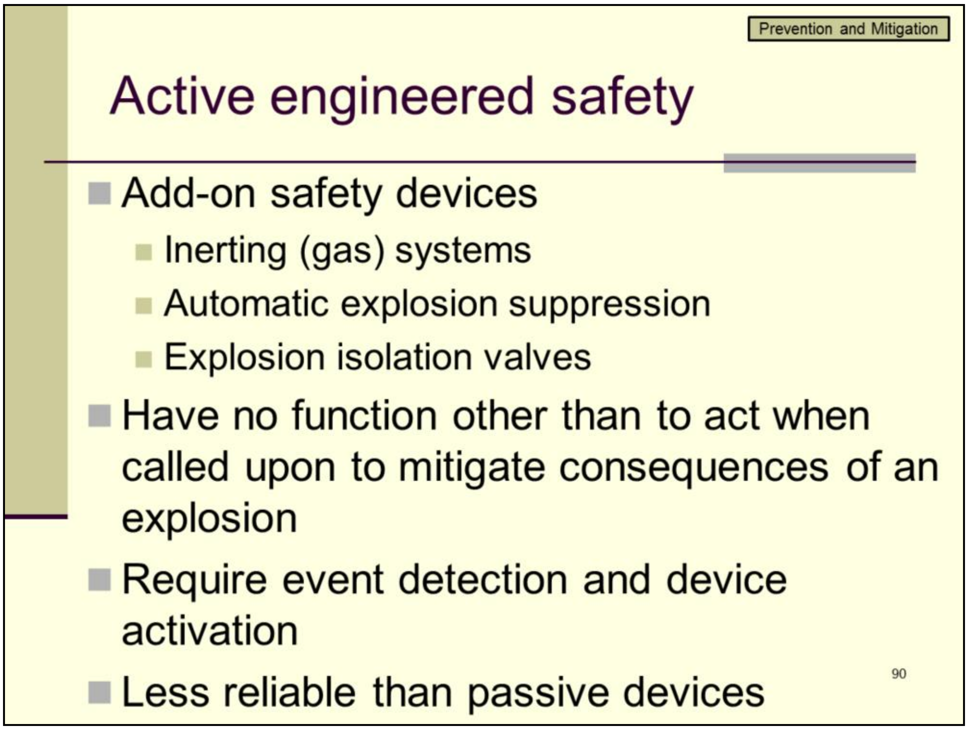
There are two concerns of note with this method of venting. First, there is a possibility of a reduction in venting efficiency as compared to the relief vent alone. Second, flameless venting into an enclosed area, such as a building, will result in increased pressure within this enclosure which may also then require venting.

Photograph: Holbrow, P., “Dust Explosion Venting of Small Vessels and Flameless Venting”, Process Safety and Environmental Protection, **91**, 183-190 (2012).

Flame quenching devices

These are pictures of typical flame quenching devices for use in the technique known as flameless venting.

Images courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).

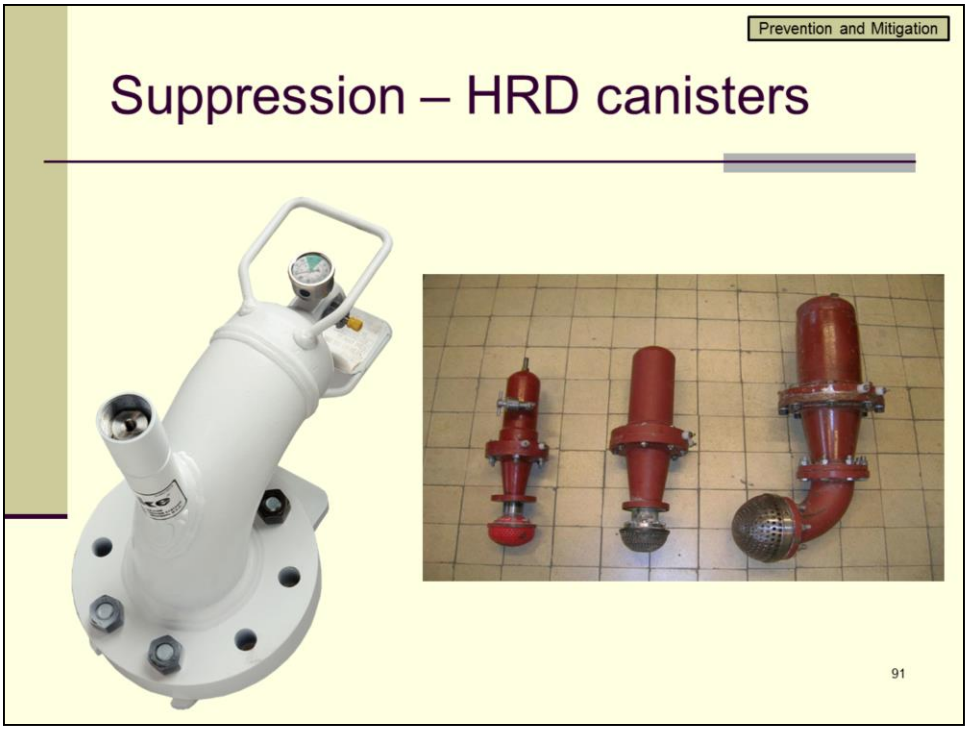


The active engineered safety level in the hierarchy of controls involves the use of safety devices that are added on to the process/facility unit. These devices do not play a production role; rather their extremely important role is to function in accordance with their design purpose to prevent explosions or mitigate explosion consequences and protect people and plant.

Active devices require detection of the explosion and activation of moving parts to perform their intended function. As such, they are less reliable than passive engineered devices (described earlier). Like any mechanical device, active engineered features must be properly designed, installed and maintained.

Examples include systems using inert gases (prevention), automatic suppression systems (mitigation), and isolation valves to limit the propagation of flame and damaging overpressures downstream (mitigation).

The use of inert gases was previously described in the Oxidant section of the module. Being preventive in nature, these systems themselves do not involve event detection and device actuation. However, they require constant monitoring of oxygen levels by other devices and are often used in conjunction with automatic suppression systems. Inert gas systems should therefore be placed in the active engineered category.



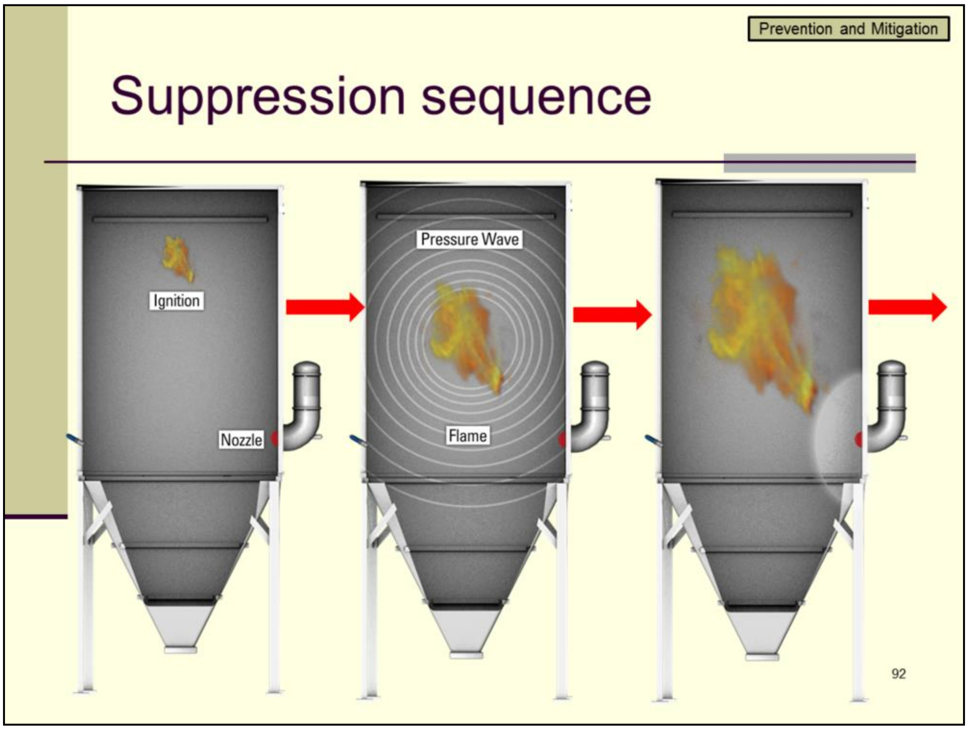
As described previously during the discussion on inherent safety, the term *inerting* arises when focusing on *preventing* the occurrence of a dust explosion; use of an inert dust admixed in sufficient amount to a fuel dust can lead to removal of the heat necessary for combustion. Also as seen previously in the module, this is analogous to explosion prevention by use of an inert gas (e.g., nitrogen) to ensure that process operation occurs at oxygen concentrations below the maximum permissible level.

On the other hand, the term *suppression* arises when focusing on *mitigating* the consequences of a dust explosion. The intent is the same as with inerting – to remove the heat necessary for sustained combustion and thus to limit the generation of destructive overpressures in an enclosed volume. In the case of suppression, however, the inert dust is injected into the just-ignited explosible dust/air mixture rather than being intimately premixed with the explosible dust prior to ignition, as in the case of inerting. Hence, suppression is an active engineered measure.

Suppression systems require the use of HRD (high-rate discharge) canisters to house the inert dust, as shown in the above pictures. The inert dust might be sodium bicarbonate or monoammonium phosphate, although in this application the material should technically be called a suppressant rather than an inertant.

Image on left courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).

Image on right from: Klemens, R., “Explosions of Industrial Dusts – From Ignition Source to Suppression”, Plenary Paper, Proceedings of Ninth International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions, Krakow, Poland (July 22-27, 2012).



The series of steps that occur during successful suppression of a dust explosion are illustrated in this slide and the next one. We see a process unit with a suppressant-containing HRD canister mounted on the exterior of the unit.

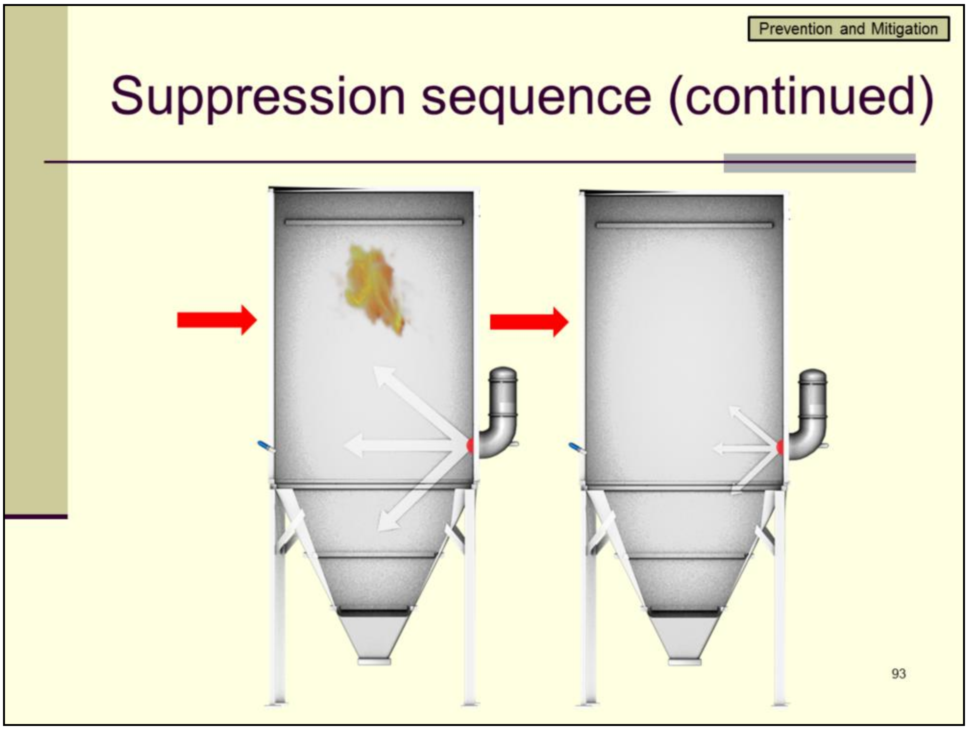
In the first figure, ignition of a cloud of combustible dust cloud has occurred. All the elements of the explosion pentagon are present.

The second figure shows flame and pressure development inside the unit. The dust explosion is in progress.

By the time of the third figure, the developing overpressure has been detected by the suppression system and a signal has been sent to release the pressurized suppressant through the nozzle.

Please go to the next slide.

Images courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).



In the first figure on this slide (fourth figure overall in the sequence), the suppressant material is being delivered into the unit. Flame is being extinguished by thermal and/or chemical means depending on the nature of the suppressant, and overpressure is being lowered.

The second figure on this slide (last figure overall in the sequence) shows a suppressed dust explosion with no flame and an intact process unit.

Images courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).

Prevention and Mitigation

Isolation valves

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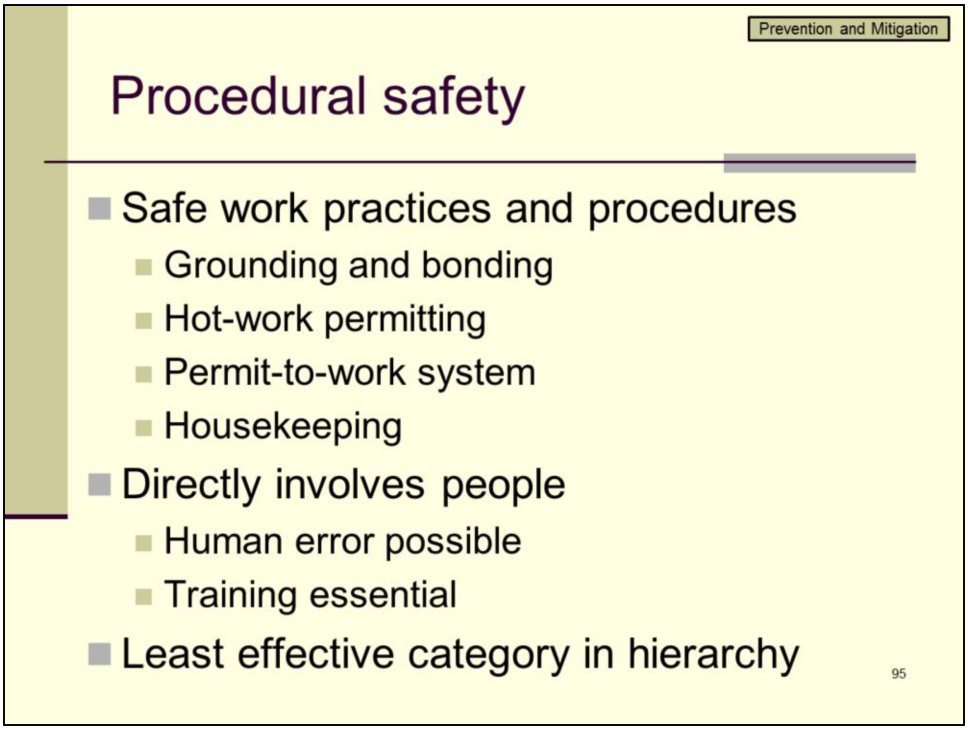
If a dust explosion occurs in a process unit, flame and pressure waves will be transmitted through connecting pipes and ducting. To protect downstream equipment, an isolation valve can be a helpful active engineered solution.

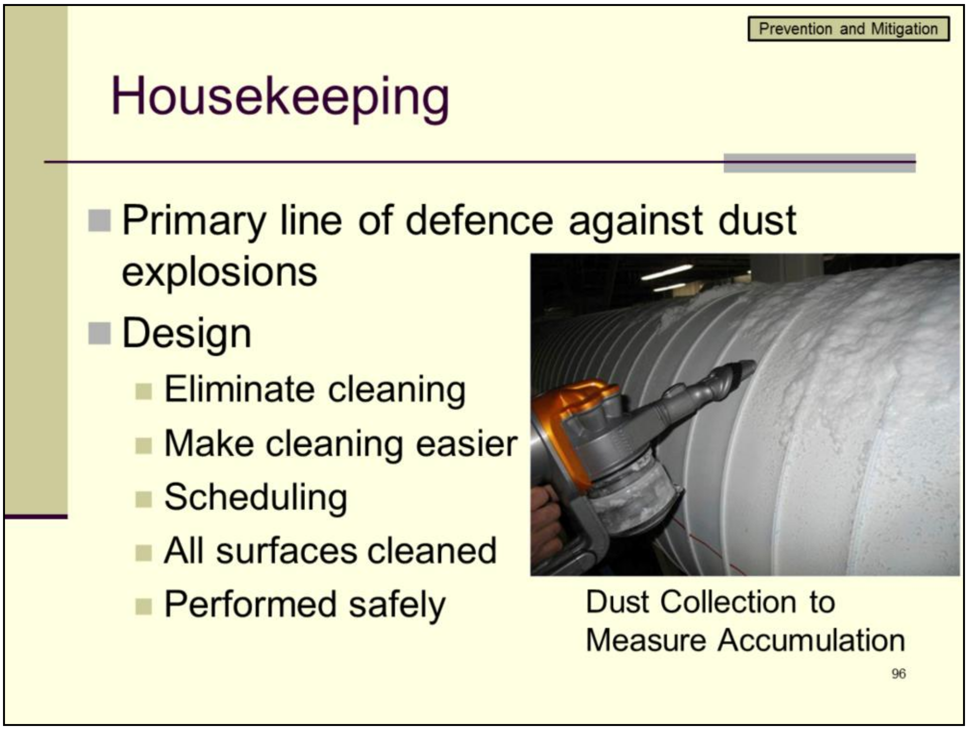
Upon pressure detection, a slide-plate rapidly closes to isolate the rest of the facility from damaging overpressures. Care must be taken to ensure that the plant is able to withstand the overpressure in the vicinity of the isolation valve.

Image courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).



Procedural safety involves people performing various tasks, often in the current context for prevention of ignition sources (electric sparks, electrostatic discharges, hot surfaces, open flames, etc.). Step-by-step procedures and more general practices such as grounding and bonding, the use of hot-work permits, and a robust permit-to-work system are all essential in this regard. Rigorous housekeeping must be performed to remove accumulated dust layers and thereby prevent dust layer fires and secondary dust explosions.

Procedural safety, although absolutely essential to the overall risk reduction approach, falls in the fourth and least effective category of the hierarchy of controls. The reason is straightforward – procedural safety involves human beings and human beings make mistakes. Human error is an ever-present possibility, and effective training and human factors programs are critical components of dust explosion prevention and mitigation efforts.



The removal of dust deposits by good housekeeping practices is a primary line of defence against dust explosions.

Frank and Holcomb (2009) offer the following advice to effectively address the housekeeping design challenge (in the desired order of application):

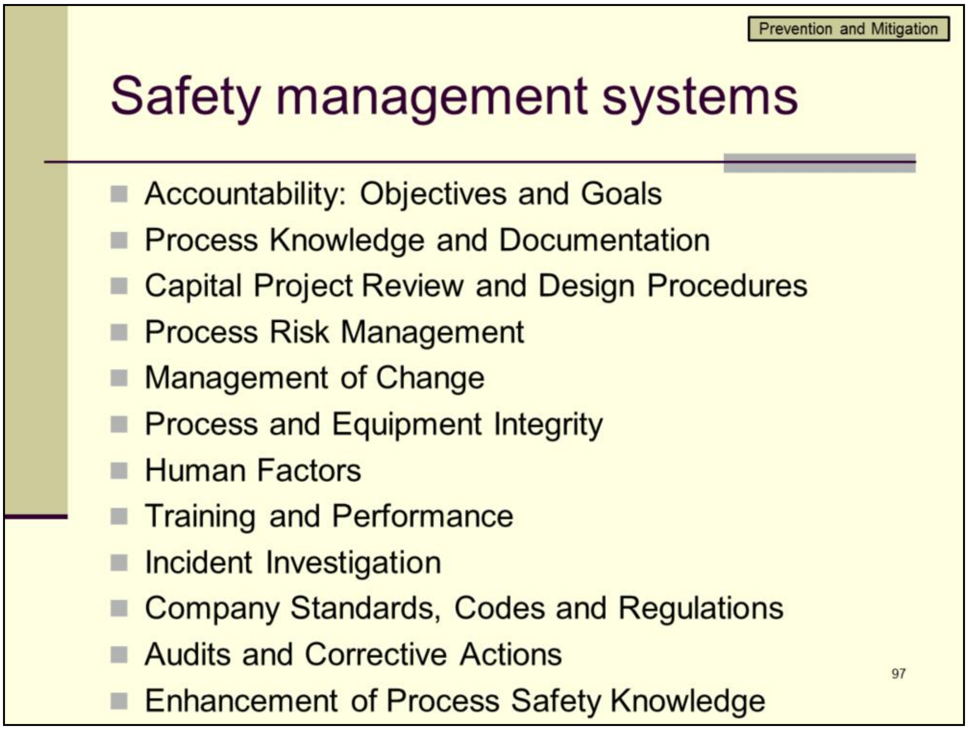
- Design and maintenance of equipment to contain dust so that it does not escape and does not have to be cleaned up,
- Dust capture at release points,
- Use of physical barriers to limit the extent of dust migration and the size of room to be cleaned,
- Facility design for easy and effective cleaning,
- Establishing and enforcing housekeeping schedules,
- Ensuring that housekeeping programs address all areas in which dust might accumulate, and
- Ensuring that housekeeping activities are performed safely.

In the words of Frank and Holcomb (2009): *The easiest/most effective housekeeping is the housekeeping you do not need to do.*

The photograph in the slide illustrates the use of a portable vacuum for dust collection from round ductwork to enable measurement of dust accumulation rates.

Photograph: Frank, W.L. and Holcomb, M.L., “Housekeeping Solutions”, Proceedings of Symposium on Dust Explosion Hazard Recognition and Control: New Strategies, The Fire Protection Research Foundation, Baltimore, MD (May 13-14, 2009).

Photograph courtesy of Kimberly-Clark Corporation.

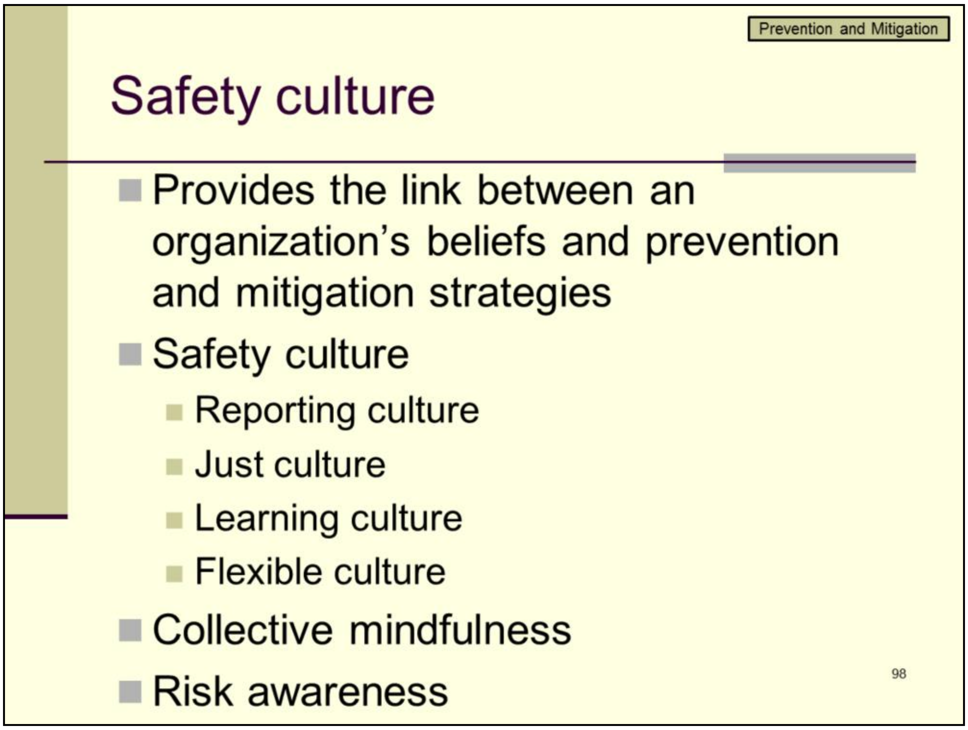


To conclude this section on prevention and mitigation of dust explosions, we make brief mention of two important concepts – safety management systems and safety culture. The mention is indeed brief, but only because a full discussion is outside the scope of the current module. There should be no doubt, however, that without the will to implement dust explosion risk reduction measures in a systematic and organized manner, all technical solutions are wasted. This statement will be borne out by the case studies explored in the next module section.

Safety management systems are recognized and accepted worldwide as best-practice methods for managing risk. They typically consist of 10 – 20 program elements that must be effectively carried out to manage the risks in an acceptable way. This need is based on the understanding that once a risk is accepted, it does not go away; it is there waiting for an opportunity to happen unless the management system is actively monitoring company operations for concerns and taking preventive actions to correct potential problems. The cycle of *plan*, *do*, *check* and *act* is the mantra of the management system approach to safety.

As a primary corporate objective, dust explosion prevention and mitigation fall within the scope of a process safety management system (i.e., a management system for process-related hazards such as fire, explosion and release of toxic materials). PSM, or Process Safety Management itself, is defined as the application of management principles and systems to the identification, understanding and control of process hazards to prevent process-related injuries and accidents.

The version of PSM recommended by the Canadian Society for Chemical Engineering (CSChE) consists of the 12 elements given in this slide. The web site of the PSM Division of the CSChE should be consulted for further information: http://www.cheminst.ca/connect/forums/psm (as of May 18, 2014).

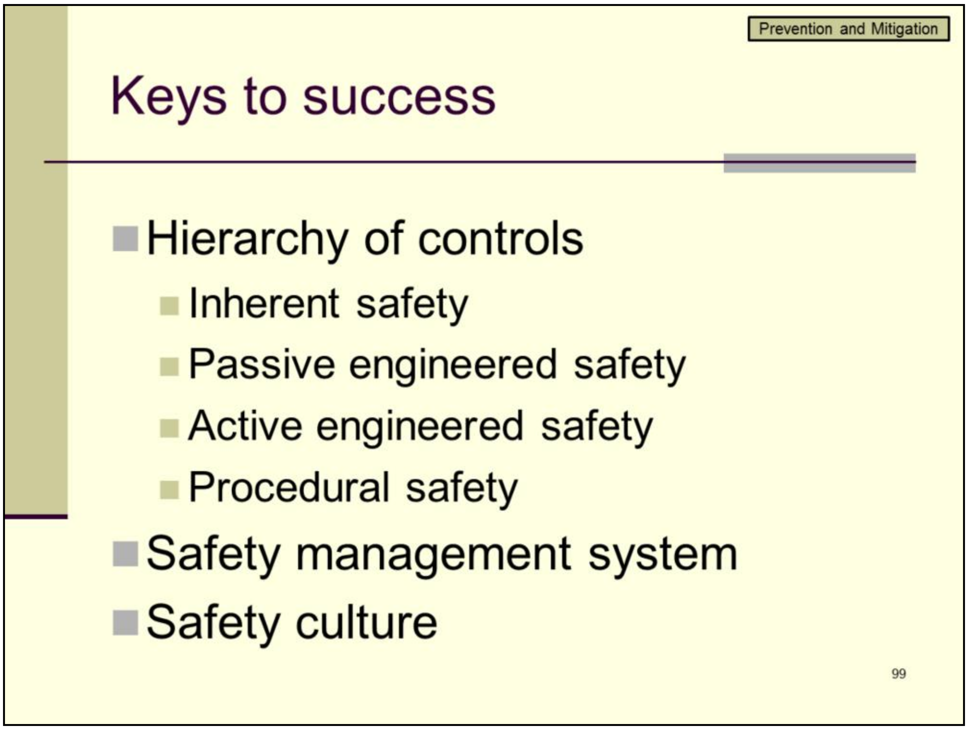


The collective beliefs of an organization regarding safety have a strong link with technical issues surrounding dust explosion prevention and mitigation. An organization with a positive safety culture will believe that they can achieve a higher safety standard and that safety is equal in importance to production.

Sociologist Andrew Hopkins (Hopkins, 2005) describes three concepts that address a company's cultural approach to safety, and makes the argument that the three are essentially alternative ways of talking about the same phenomena: (i) safety culture, (ii) collective mindfulness, and (iii) risk-awareness.

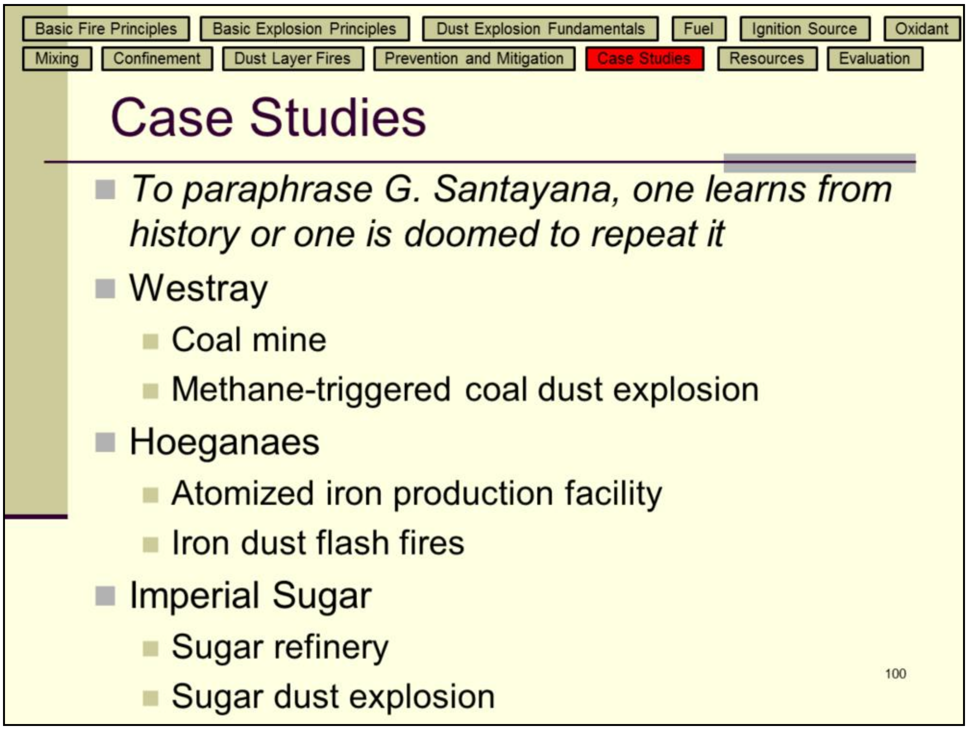
He further defines a safety culture as embodying the following subcultures: (i) a *reporting culture* in which people report errors, near-misses, and substandard conditions and practices, (ii) a *just culture* in which blame and punishment are reserved for behaviour involving defiance, recklessness or malice, such that incident reporting is not discouraged, (iii) a *learning culture* in which a company learns from its reported incidents, processes information in a conscientious manner, and makes changes accordingly, and (iv) a *flexible culture* in which decision-making processes are not so rigid that they cannot be varied according to the urgency of the decision and the expertise of the people involved.

Reference: Hopkins, A., “Safety, Culture and Risk. The Organizational Causes of Disasters”, CCH Australia Limited, Sydney, Australia (2005).



In summary, a dust explosion risk reduction program must incorporate the following elements to be successful:

- Hierarchy of controls,
- Safety management system, and
- Safety Culture



The quote paraphrasing G. Santayana is taken from the following reference: Crowl, D. A. and Louvar, J. F., "Chemical Process Safety. Fundamentals with Applications", 3rd edition, Prentice Hall PTR, Upper Saddle River, NJ (2011).

Case studies are extremely helpful in enhancing the overall safety initiative. They incorporate the concept of *lessons learned* as the primary motivation for their use. This usually means that the most effective case studies are those giving details of a failure or shortcoming of some sort; it is human nature to pay attention when a story is being told and a loss – whether catastrophic or not – is involved. The quote from Crowl and Louvar (2011) illustrates the importance of learning from case histories and avoiding hazardous situations; the alternative is to ignore the mistakes of others and be involved in potentially life-threatening incidents.

In this section of the module, we briefly present three case studies. The incidents have been selected to cover a range of industries, fuels and event types. Further details can be found in the primary references identified for each incident.

Case Studies

Westray: what happened

Methane-triggered coal dust explosion

Plymouth, NS

May 9, 1992

26 fatalities

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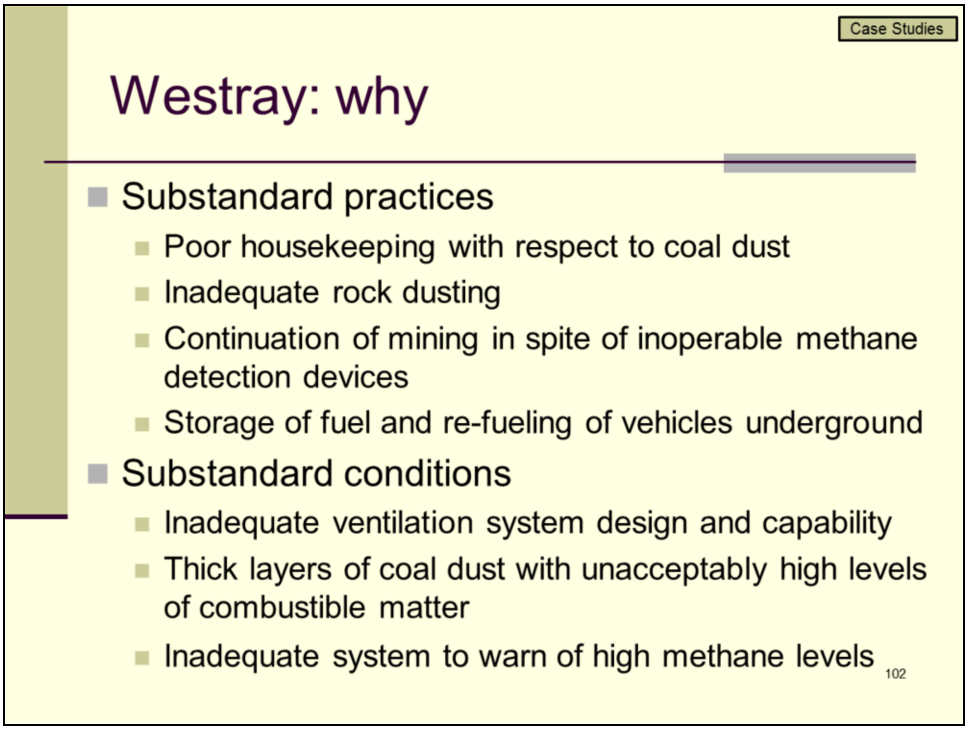
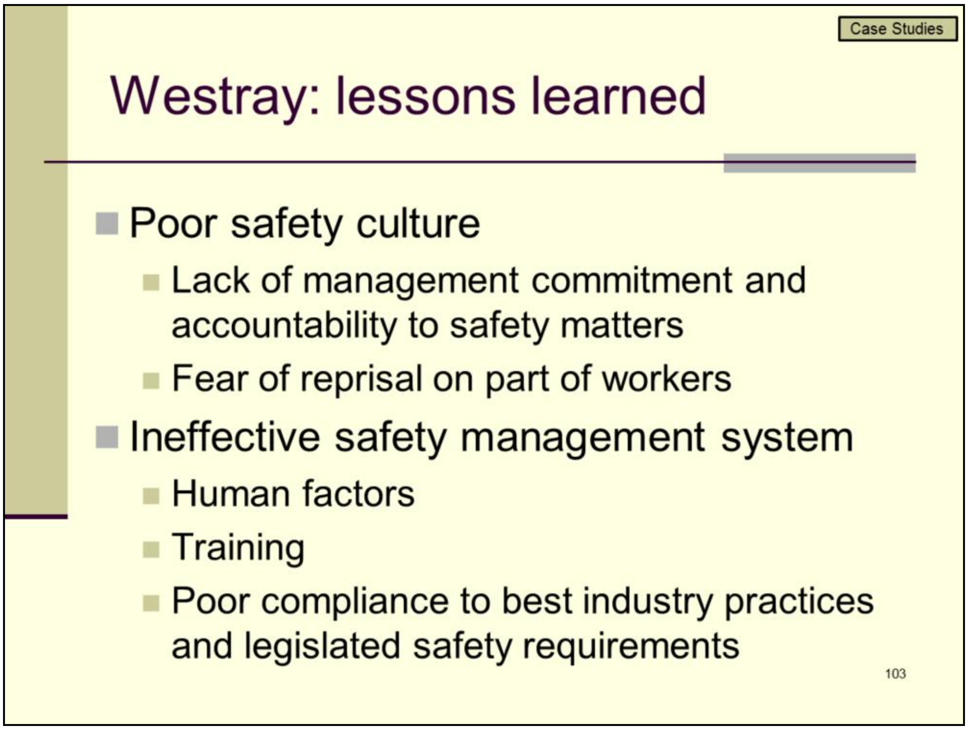
Primary References

Richard, K.P., Justice, “The Westray Story – a Predictable Path to Disaster. Report of the Westray Mine Public Inquiry”, Province of Nova Scotia, Halifax, NS (1997).
Amyotte, P.R. and Oehmen, A.M., “Application of a Loss Causation Model to the Westray Mine Explosion”, Process Safety and Environmental Protection (Transactions of the Institution of Chemical Engineers, Part B), **80**, 55-59 (2002).

Westray was an underground coal mine in Plymouth, Nova Scotia (just outside of New Glasgow). On May 9, 1992 a methane-triggered coal dust explosion occurred, resulting in twenty-six fatalities. The overpressures generated underground were powerful enough to result in damage at the surface, as we can see in this photograph from the public inquiry report (Richard, 1997).



With its poor working conditions, Westray was an incident waiting to happen. Inadequate mine ventilation resulted in methane concentrations that were consistently higher than those permitted by regulations. Coal dust accumulation levels were also high, and there was a lack of rock dusting (inerting of the coal dust with limestone or dolomite). As indicated in the slide, other standard practices were also occurring in the mine (Amyotte and Oehmen, 2002).



These substandard practices and conditions were a result of the lack of concern management had with respect to safety issues at the mine.

There was a poor safety culture at Westray, and production was prioritized at the expense of employee safety. Employees had a fear of reprisal, which undermined the possibilities for just and reporting cultures, and did not provide an opportunity for the existence of learning and flexible cultures.

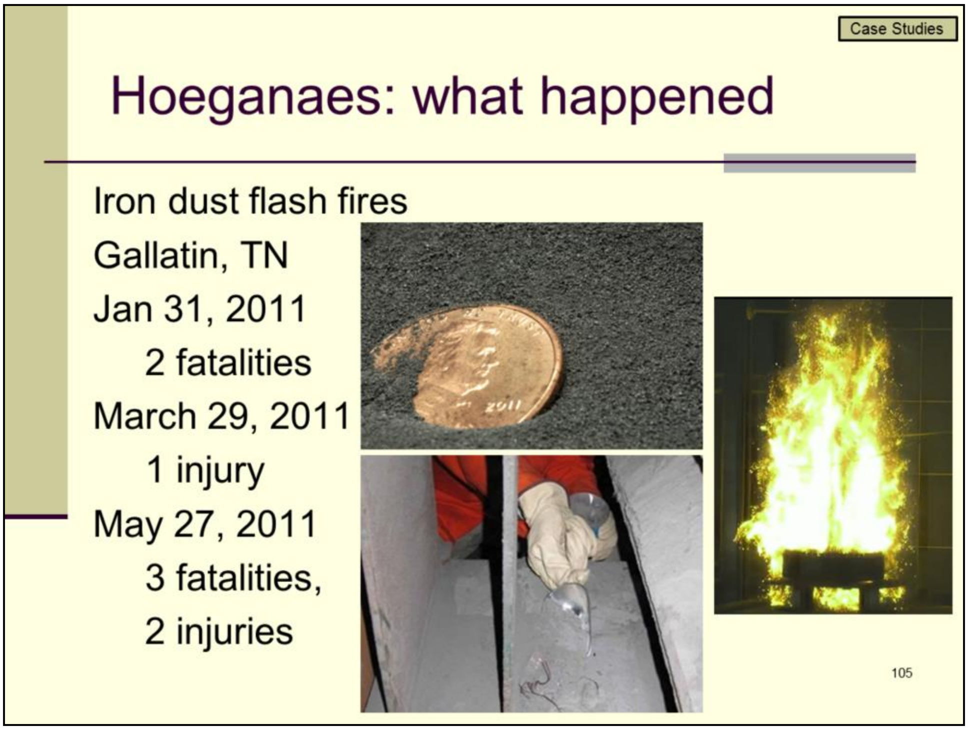
Additionally, there was no effective safety management system at Westray. Employees generally had a lack of experience and knowledge of safe underground working practices. There was also a lack of safe work practices and procedures in place, indicating that employees were poorly trained.

Westray clearly demonstrates that a safety management system approach and the concept of safety culture go hand-in-hand when it comes to assuring worker safety (Amyotte and Oehmen, 2002).

Workers paid the ultimate price for management’s shortcomings at Westray. This is a photograph of the Westray Memorial in New Glasgow, NS (photograph courtesy of United Steelworkers; photograph by Peter Boyle). The Memorial displays a miner’s lamp with thirteen rays of light emanating from each side of the lamp. Each ray contains the name and age of a Westray miner killed in the explosion.

Westray has left an indelible legacy on the people of Nova Scotia and Canada. It is widely accepted that the structure of the current Nova Scotia Occupational Health and Safety Act was hugely influenced by the Westray coal mine explosion. Bill C-45, a 2004 amendment to the Canadian Criminal Code, is known colloquially as the “Westray Bill” or “Westray Amendment”. According to the Canadian Centre for Occupational Health and Safety, Bill C-45

- Created rules for establishing criminal liability to organizations for the acts of their representatives, and
- Establishes a legal duty for all persons "directing the work of others" to take reasonable steps to ensure the safety of workers and the public.



<u>Primary Reference</u>

CSB, “Case Study. Hoeganaes Corporation: Gallatin, TN. Metal Dust Flash Fires and Hydrogen Explosion”, No. 2011-4-I-TN, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2011).

The material on the notes pages for the Hoeganaes case is drawn from the above CSB report (CSB, 2011). Photographs shown on the slides can be found in the report (CSB, 2011) or on the CSB web site (www.csb.gov).

Hoeganaes Corporation is a producer of atomized steel and iron powders. In 2011, there were three flash fire incidents at the Hoeganaes facility in Gallatin, Tennessee. This particular Hoeganaes plant manufactured atomized iron powder for the production of metal parts in the automotive and other industries. The first incident occurred when a bucket elevator was restarted. Iron dust was dispersed into the air and ignited; the resulting flash fire killed two workers. The second incident occurred while igniters were being replaced on a band furnace. A hammer was being used to force reconnection of a gas port, in the process dispersing dust from a surface on the side of the furnace. The dust ignited and the ensuing flash fire injured one employee. In the third incident (described in more detail later in this case study presentation), a hydrogen explosion and resulting iron dust flash fires, claimed three lives and injured two other workers.

The photographs show fine iron dust present at the facility (with a penny for scale); layered iron dust observed post-explosion; and a laboratory-scale demonstration of an iron dust flash fire.

Case Studies

Hoeganaes: why

- No employee training
- Accumulations of iron dust
  - Inadequate housekeeping
  - Elevated surfaces

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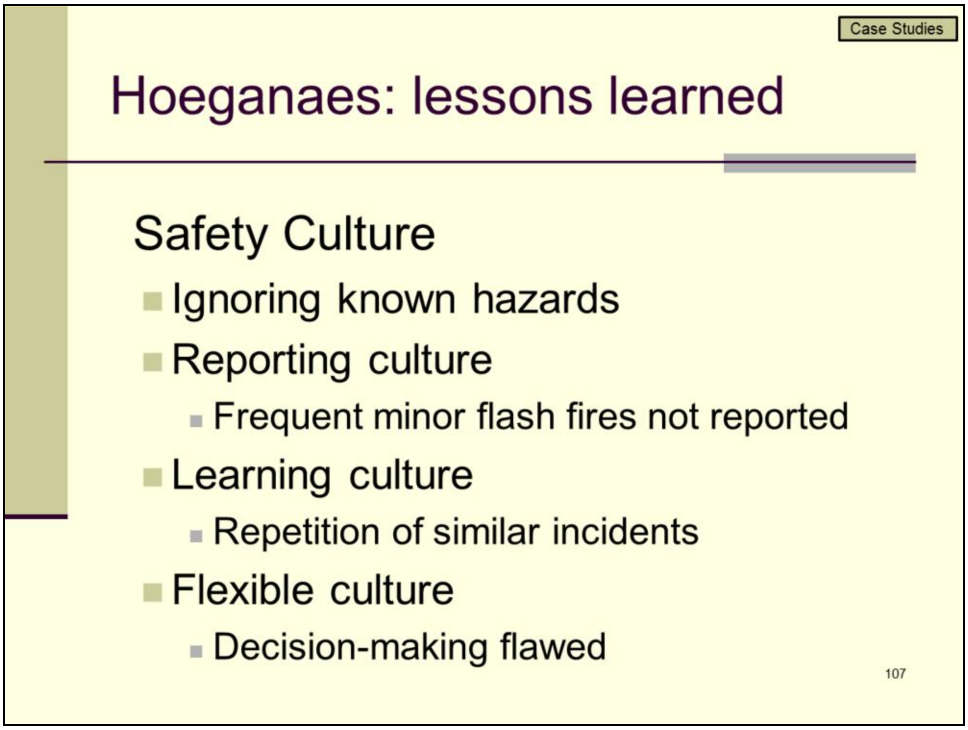
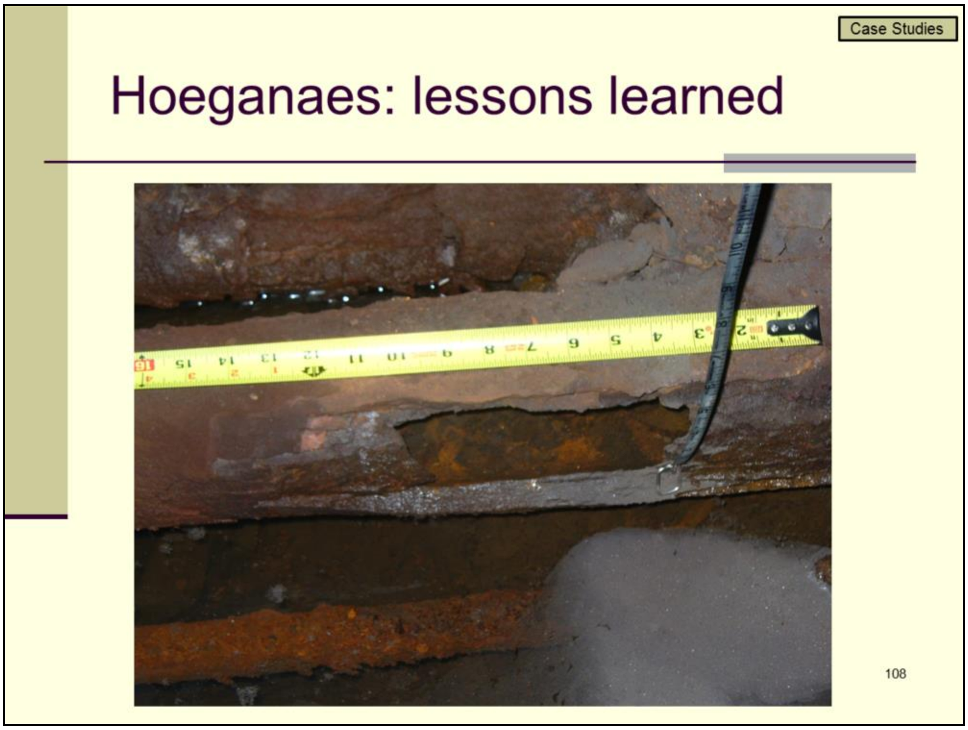
Although employees were aware that iron dust flash fires could occur, they were not trained to appreciate the potential severity of such events or to identify combustible dust hazards. There were also significant accumulations of combustible iron dust throughout the facility. Dust collection systems were unreliable, housekeeping procedures were inadequate, and there were numerous elevated surfaces on which dust could accumulate (one of which is shown in the photograph).



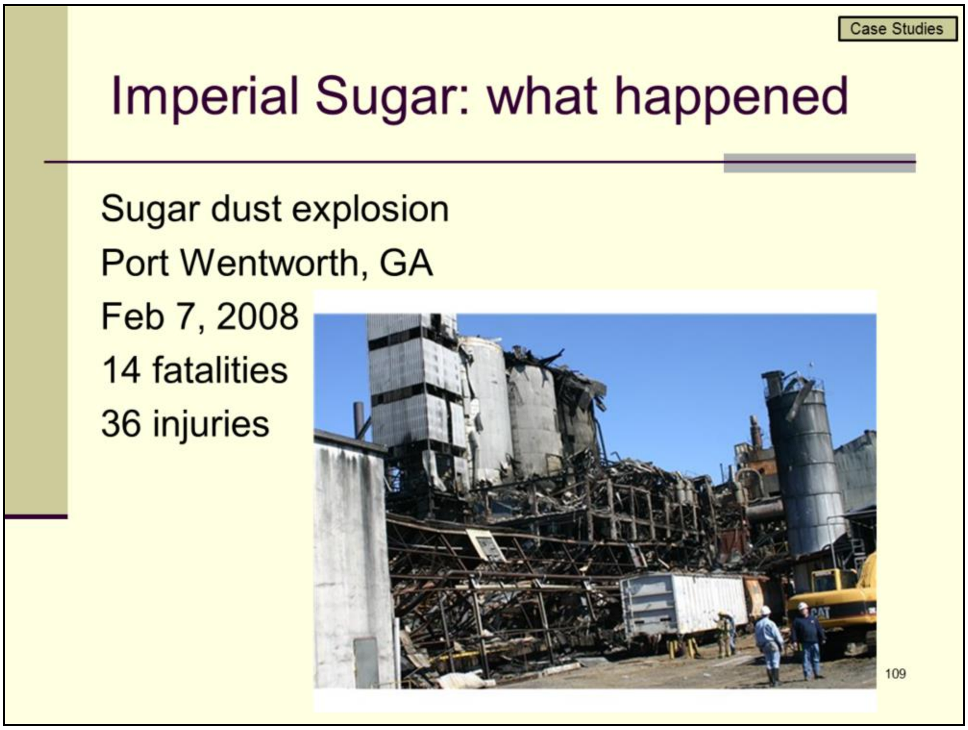
There were issues with safety culture at Hoeganaes. Management was aware prior to the first incident in 2011 that there were combustion hazards associated with the iron dust in the facility, yet no actions were taken to mitigate these hazards. Flash fires occurred periodically at the plant, but prior to the incident in January 2011 there had been no serious injuries. Thus, the incidents became normalized and minor flash fires and near-misses were not reported. Three major incidents in such a short period of time, in addition to many previous minor events, indicate that nothing was learned and that known combustible dust hazards were not addressed. Decisions leading up to the incidents were not made by those most knowledgeable, and were made with little thought to possible consequences. This is clear from the description of the third incident – a hydrogen explosion and iron dust flash fires – given in the next slide.



The third incident was initiated by a hydrogen leak in a process-pipe trench. (Hydrogen was used in the plant's continuous annealing furnaces to prevent oxidation of the iron powder). The hole in the pipe can be seen in the photograph. The trench held nitrogen piping and cooling water runoff in addition to the hydrogen piping. When a leak within the trench was identified, it was assumed to be the nitrogen pipe leaking as a result of a recent nitrogen leak elsewhere in the facility. There were no procedures in place to mitigate gas leaks. Even though it was known that hydrogen piping was also present in the trench, no effort was made to test the atmosphere to determine the source of the leak. Maintenance personnel opted to remove trench covers to identify the source of the leak. They used a forklift to remove the trench covers, which created frictional sparking that ignited the accumulated hydrogen gas. The explosion overpressure dispersed iron dust from elevated surfaces, igniting the dust and creating multiple flash fires.

Just as some people are surprised to learn that a dust can actually explode, some are also surprised by the fact that metal dusts can explode. Some metals such as fine, unoxidized aluminum powder are highly reactive and are among the most hazardous of combustible dusts. Other metals such as iron dust have higher ignition energies and generate lower overpressures and rates of pressure rise. Given the relatively low reactivity of the iron dust at Hoeganaes and the limited confinement in the plant building, it is not surprising that flash fires rather than dust explosions occurred. But consider these questions:

- What if the iron dust had been finer and therefore more reactive?
- What if the degree of confinement or the blockage ratio had been greater?
- Does it really matter to an injured party whether the injuries were caused by a flash fire or by an explosion?

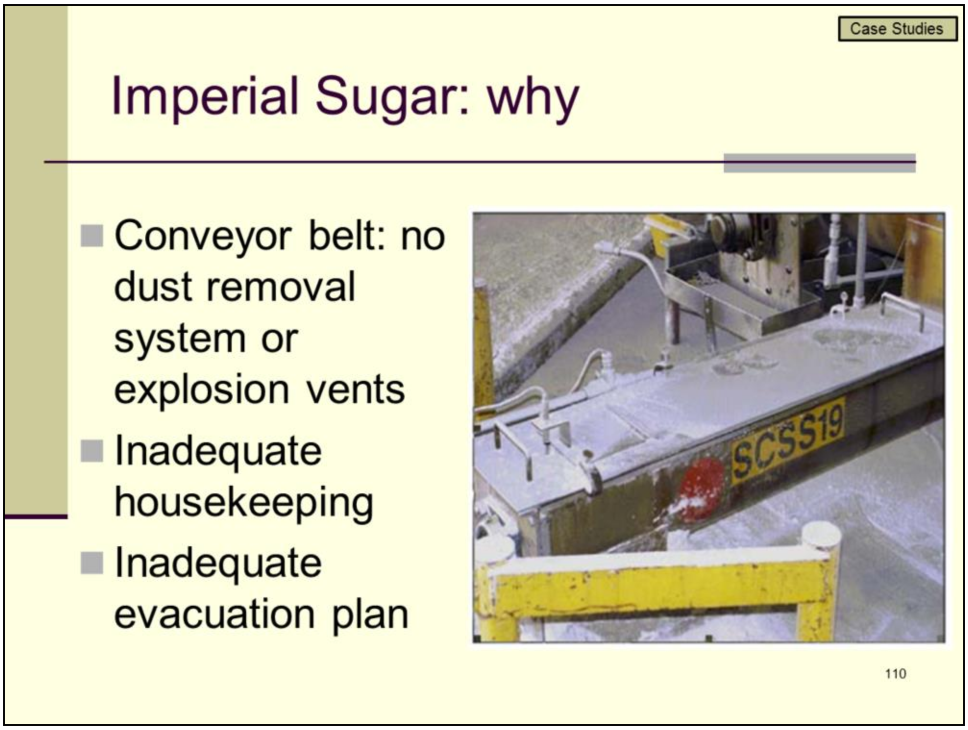


Primary Reference

CSB, "Investigation Report. Sugar Dust Explosion and Fire. Imperial Sugar Company", Report No. 2008-05-I-GA, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2009).

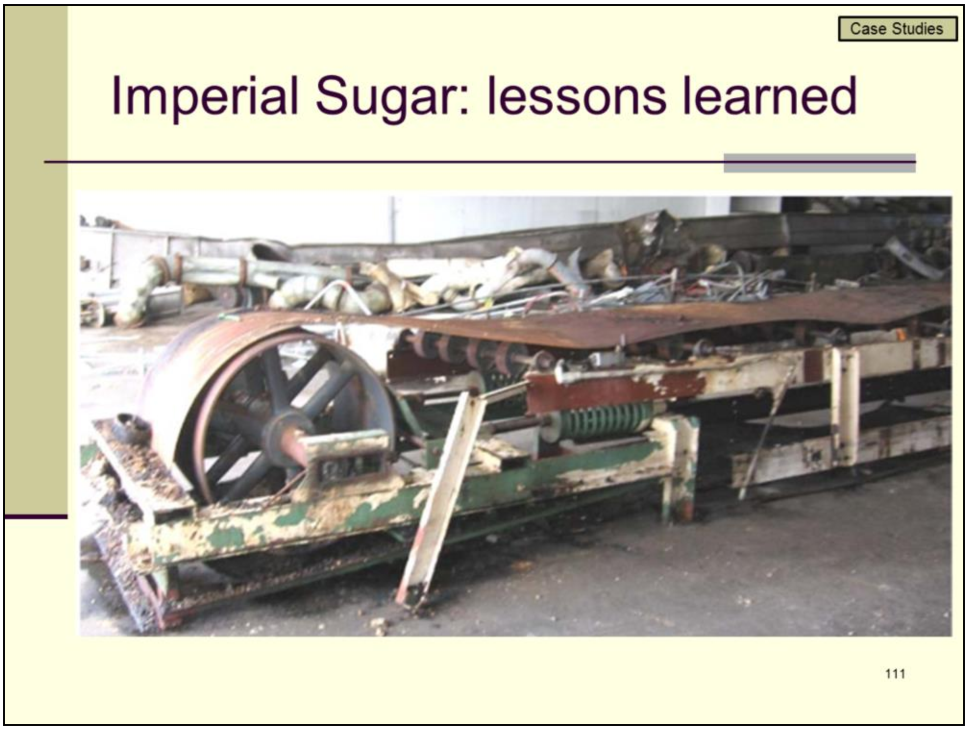
The material on the notes pages for the Imperial Sugar case is drawn from the above CSB report (CSB, 2009). Photographs shown on the slides can be found in the report (CSB, 2009) or on the CSB web site (www.csb.gov).

The Imperial Sugar Company in Port Wentworth, Georgia, refined raw sugar into granulated sugar and packaged the final product. On February 7, 2008 a primary dust explosion occurred inside an enclosed conveyor belt under several storage silos. This event triggered multiple secondary explosions that propagated through the packaging buildings, bulk sugar loading buildings, and parts of the raw sugar refinery. Concrete floors buckled, a wooden roof collapsed, and sprinkler systems failed because the explosion had ruptured the water pipes. Employees had no time to react. Eight workers died at the scene, four of whom were trapped by falling debris and collapsing floors. Nineteen workers were severely burned and six later succumbed to their injuries.



The conveyor belt where the primary explosion occurred was enclosed to prevent contamination. However, it was not equipped with a dust removal system or explosion relief vents. Routine housekeeping procedures were not implemented at the facility. As such there were significant accumulations of sugar and sugar dust in the refinery, as shown in the photograph. Compressed air was used for housekeeping, resulting in dust accumulations on elevated surfaces. It is believed that the secondary explosions and resulting damage and fatalities would likely not have occurred if proper housekeeping procedures had been enforced.

The emergency evacuation plan was also inadequate. This deficiency, along with poor lighting, large pieces of equipment and conveyors on or near the floor, and no emergency alarm system, all hindered the evacuation and safety of employees.



This photograph shows a conveyor belt removed after the incident. The granulated sugar on conveyor belts had previously been exposed to possible contamination from falling debris, and so in 2007 the conveyor belts were enclosed with top and side panels. While this addressed the issue of contamination, it inadvertently created a much higher level of confinement. This is an example of inadequate safety management, specifically management of change, where a new hazard was introduced as a result of a change to process equipment.

The high concentrations of sugar dust in such a relatively small enclosure created an ideal environment for a dust explosion, yet as previously mentioned – no dust removal systems, explosion vents, or other prevention and mitigation strategies were implemented. As a result, a primary explosion occurred within the enclosure, causing several secondary explosions and fires to propagate through the facility. Management of change, or MOC, is one of the most important safety management system elements to consider in a processing facility.

Case Studies

Imperial Sugar: lessons learned

- Previous fires and near-misses
- Management knew about hazards

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There were previously reported incidents of fires and near-misses. Two weeks prior to the 2008 catastrophic explosion, there was a small explosion in a dust collector, which had been safely vented. Management was therefore aware of the existing hazards at the facility. However, plans for improvements in the past, such as with housekeeping procedures, were either forgotten or neglected. The refinery was able to function successfully despite unfavorable conditions, since any incidents to-date had always been relatively minor. Rather than attempting to identify and correct underlying causes, evidence of deviations was accepted and normalized.

The photograph (circa 1990) illustrates that the issues surrounding housekeeping were a longstanding problem at this facility.

A large amount and variety of resources on dust explosions are available. Here we present examples of resource material in the form of a video, incident investigation reports, an explosion parameter data base, testing and risk control standards, peer-reviewed journal papers, and text books.

Video
Marta, M., “Probable Dust Explosions in B.C. Opportunity to Understand Possible Contributing Factors, At-Risk Industries, Basic Safeguarding Measures, Standards, Regulations”, 62nd Canadian Chemical Engineering Conference, Vancouver, BC (2012).
Available at: http://vimeo.com/50925194 (last accessed May 9, 2014).
This video will be helpful in considering the Babine Forest Products incident as part of the Evaluation (Analyzing) exercise in the next module section.

Incident Investigation Reports
Another excellent resource is the web site of the United States Chemical Safety and Hazard Investigation Board (Chemical Safety Board or CSB): www.csb.gov. This web site contains all of the CSB reports referenced in the module as well as additional investigation reports of dust explosion incidents. The more recent reports are typically accompanied by an explanatory video.

Explosion Parameter Data Base
The IFA GESTIS-DUST-EX data base contains values of explosion parameters for many dusts. A cautionary note must be made, however, that there is no substitute for standardized-test data for a given dust being handled in industry.
Available at: http://www.dguv.de/ifa/Gefahrstoffdatenbanken/GESTIS-STAUB-EX/index-2.jsp (last accessed May 9, 2014).

Testing Standards
The dust explosibility testing standards referenced in the module (and others) are available on the ASTM International web site: www.astm.org. As of May 9, 2014, there is a fee to download these standards.

Risk Control Standards
The risk control standards referenced in the module (and others) are available on the National Fire Protection Association (NFPA) web site: www.nfpa.org. As of May 9. 2014, there is no fee to download these standards.

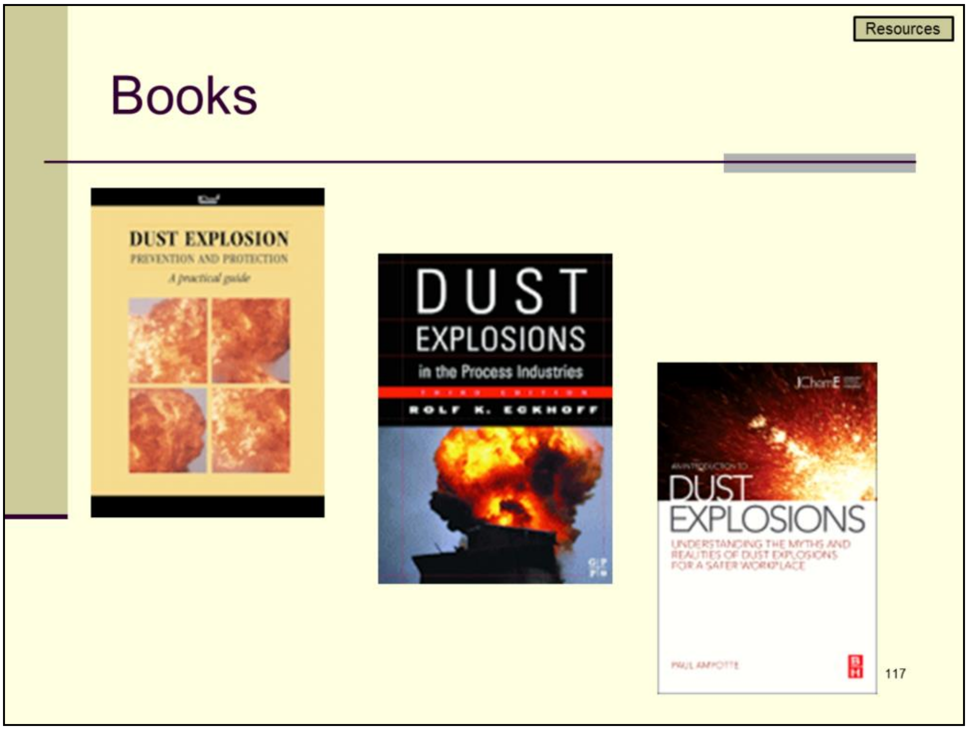
<u>Peer-Reviewed Journal Papers</u>

Abbasi, T. and Abbasi, S.A., “Dust Explosions – Cases, Causes, Consequences, and Control”, Journal of Hazardous Materials, **140**, 7-44 (2007).

Eckhoff, R.K., “Understanding Dust Explosions. The Role of Powder Science and Technology”, Journal of Loss Prevention in the Process Industries, **22**, 105-116 (2009).

Amyotte, P.R. and Eckhoff, R.K., “Dust Explosion Causation, Prevention and Mitigation: an Overview”, Journal of Chemical Health and Safety, **17**, 15-28 (2010).

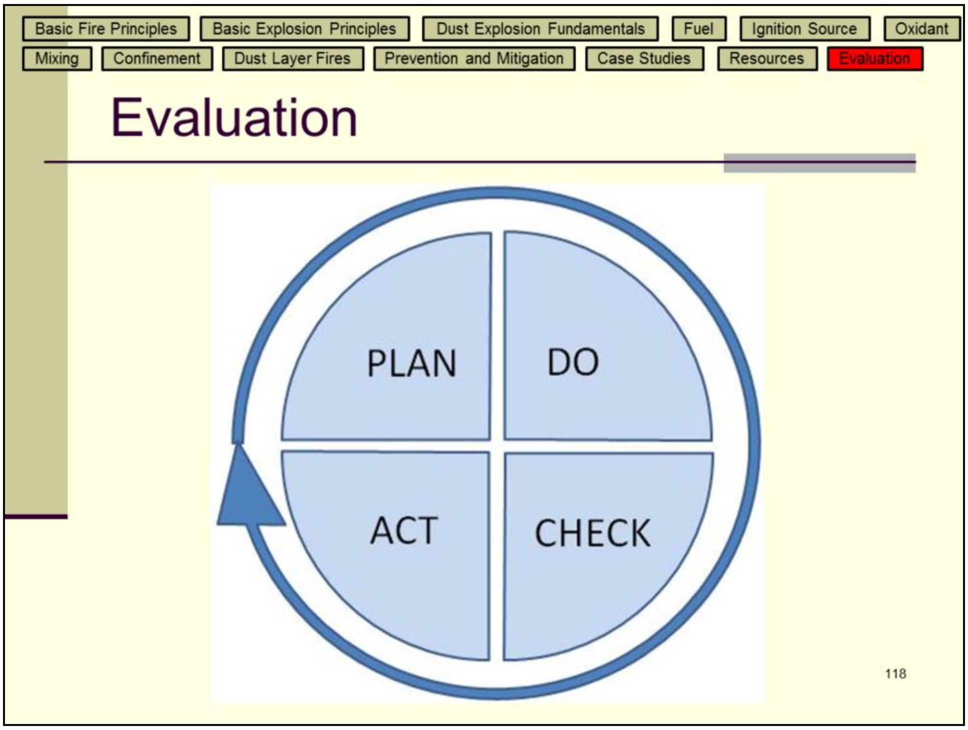
Amyotte, P.R., “Some Myths and Realities about Dust Explosions”, Process Safety and Environmental Protection (2014),http://dx.doi.org/10.1016/j.psep.2014.02.013.



Text Books
Barton, J. (editor), “Dust Explosion Prevention and Protection. A Practical Guide”, Institution of Chemical Engineers, Rugby, UK (2002).

Eckhoff, R.K., “Dust Explosions in the Process Industries”, 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).

Amyotte, P., “An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace”, Elsevier/Butterworth-Heinemann, Waltham, MA (2013).



"Plan, Do, Check, Act" is the continuous improvement cycle that characterizes all safety management efforts. Work is planned and performed, and the results are checked and acted upon for commendation or correction. In that same spirit, this evaluation section of the module is aimed at checking whether the learning objectives identified at the outset have been achieved.

Recall that these learning objectives are structured according to Bloom's Taxonomy. The next three slides address the three lower levels in the taxonomy: remembering, understanding and applying. The questions are closed-ended and the answers are brief and fairly well-defined. The subsequent three slides address the three higher levels in the taxonomy: analyzing, evaluating and creating. The questions are open-ended and the answers are longer and more involved. The information required to answer all of these questions can be found in the module and associated readings.

Evaluation

Remembering

Define what is meant by a "combustible dust".

Identify all of the elements of the fire triangle and the explosion pentagon.

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Evaluation

Understanding

Explain how a gaseous, liquid or solid fuel actually burns. (What is the physical state of the reacting fuel?)

Describe the fundamentals of a dust explosion according to the explosion pentagon.

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Evaluation

Applying

Calculate the airborne concentration in an enclosure with a height of 5 m resulting from the dispersion of a 0.8-mm thick layer of corn flour having a bulk density of 0.82 g/cm^3.

Evaluation

Analyzing

Identify the possible fuel sources that could have been involved in the explosion at the Babine Forest Products facility in Burns Lake, BC on January 20, 2012. Discuss which of these involved combustible dust hazards.

Note: This incident was investigated by WorkSafeBC; the investigation report is available on their web site: www.worksafebc.com.

Evaluation

Evaluating

Determine several strategies that might have been helpful in preventing and mitigating the polyethylene dust explosion at the West Pharmaceuticals facility in Kinston, NC on January 29, 2003. Be sure to justify your choices.

Note: This incident was investigated by the US Chemical Safety Board; the investigation report is available on their web site: www.csb.gov.

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Evaluation

Creating

Formulate a dust explosion prevention plan for the scenario described below. Be sure to account for each element of the explosion pentagon.

? ? ?

A fine aluminum powder is being processed at a facility involving numerous physical operations such as grinding, pulverizing and sieving. Workers are largely unaware of combustible dust hazards and plant management has not shown itself to be very supportive of loss prevention efforts.